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# REDUCING GREENHOUSE GAS EMISSIONS IN RANGELANDS THROUGH LANDSCAPE-BASED MANAGEMENT

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# Reducing Greenhouse Gas Emission in Rangelands Through Landscape-based Management

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For the Period of
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# Abstract

Three experiments were conducted between 2003 and 2005 in central and southern Saskatchewan to determine greenhouse gas (GHG) emissions and soil carbon as affected by factors such as landscape element, grazing and shrub invasion. The areas studied include the Mixed Grassland and Moist Mixed Grassland Ecoregions within the Prairie Ecozone. The site for the GHG emissions study was located near Macrorie, SK, within the Missouri Coteau. Landscape elements such as north facing concave aspect, north facing convex aspect, south facing concave aspect, level upland and depression were selected within the hummocky landscapes. Defoliation treatment was imposed in April to simulate grazing effect. The flux rates of $CO_2$, $CH_4$, and $N_2O$ were lower than arable lands in Saskatchewan and fluctuated in response to changes in soil water and soil temperature. Landscape element significantly affected the flux of $CO_2$, $CH_4$, and $N_2O$. The largest production of $CO_2$ and $N_2O$ and the largest consumption of $CH_4$ were recorded on the depression. Mowing increased $CO_2$ emissions, $CH_4$ consumption and $N_2O$ production. Aspect was negatively correlated with $CH_4$ flux, while slope shape was positively correlated with $CO_2$ flux. Biophysical characteristics such as soil temperature and water content, as well as plant species composition also varied among landscape elements, contributing to variations in GHG fluxes. Nine sites were selected for the effect of shrub invasion on soil carbon and results show that along the gradient from grassland to shrub communities, soil organic carbon (SOC) had less than 5% increase, which was not significant. Large root biomass but not medium or small root biomass was higher in the shrub community than the others. Another nine sites were selected for the effect of cattle grazing on soil carbon. Grazing did not significantly affect SOC and root biomass, even though it SOC tended to be lower at the grazed sites than the ungrazed. For all 18 sites studied, SOC was the most important carbon pool and was higher than the combination of above- and below ground biomass. Soil carbon was controlled more by soil texture than by shrub cover or grazing with loamy soils having greater SOC and root biomass than sandy soils. Results from this project indicate that GHG emissions from native grasslands are relative small. Changes in vegetation from grassland to shrubland increased above-ground biomass but not SOC and grazing did not significantly alter soil carbon. Therefore, current management practices aiming at sustainability and integrity of grassland ecosystems should be maintained.

# Executive Summary

Global climate change has been linked to the increase in atmospheric concentrations of greenhouse gases (GHG) due to the burning of fossil fuels, deforestation and changes in land use. Grasslands and their utilization contribute to GHG emissions and determining the controls and magnitude of GHG flux in grasslands helps Canada comply with internationally agreed upon emission reduction targets. GHG emissions from grasslands especially whose with hummocky terrain are understudied possibly due to the complex interactions of landscape element, physical characteristics, disturbance and plant community, all of which vary in space and time. Objectives of this study were: 1) to contrast the spatial variability in GHG emissions between protected and defoliated rangelands in Saskatchewan, 2) to model landscape-level variations in GHG emissions and to correlate GHG with landscape elements, biophysical factors, plant species diversity, and forage production, 3) to determine the relationship between range condition and soil carbon as well as the effect of shrub invasion on soil carbon, and 4) to provide baseline data for optimal pasture management to maximize the economic and ecological returns.

Three experiments were conducted between 2003 and 2005 in central and southern Saskatchewan to determine greenhouse gas (GHG) emissions and soil carbon as affected by factors such as landscape element, grazing and shrub invasion. The areas studied include the Mixed Grassland and Moist Mixed Grassland Ecoregions within the Prairie Ecozone. The site for the GHG emissions study was located near Macrorie, SK, within the Missouri Coteau. Landscape elements such as north facing concave aspect, north facing convex aspect, south facing concave aspect, level upland and depression were selected within the hummocky landscapes. Defoliation treatment was imposed in April to simulate grazing effect. Carbon dioxide, $CH_4$ and $N_2O$ were measured every 7-10 days from spring until fall with closed, vented chambers. Soil $CO_2$ flux ranged from 3.2 to 19.7 kg $CO_2$-C $ha^{-1}$ $d^{-1}$ among the control landscape elements and 1.8 to 22.8 kg $CO_2$-C $ha^{-1}$ $d^{-1}$ among the mowed landscape elements. Soils were a net sink for $CH_4$, consuming 1.0 to 4.4 g $CH_4$-C $ha^{-1}$ $d^{-1}$ among the control landscape elements and 1.8 to 4.6 g $CH_4$-C ha-1 d-1 among the mowed landscape elements. Nitrous oxide flux ranged from -0.20 to 0.79 g $N_2O$ -N ha-1 d-1 among control landscape elements and -0.33 to 0.92 g $N_2O$ -N $ha^{-1}$ $d^{-1}$ among mowed landscape elements. The flux rates of $CO_2$, $CH_4$, and $N_2O$ were lower than arable lands in Saskatchewan and fluctuated in response to changes in soil water and soil temperature. Landscape element significantly affected the flux of $CO_2$, $CH_4$, and $N_2O$. The largest production of $CO_2$ and $N_2O$ and the largest consumption of $CH_4$ were recorded on the depression. Mowing increased $CO_2$ emissions, $CH_4$ consumption and $N_2O$ production. Aspect was negatively correlated with $CH_4$ flux, while slope shape was positively correlated with $CO_2$ flux. Biophysical characteristics such as soil temperature and water content, as well as plant species composition also varied among landscape elements, contributing to variations in GHG fluxes.

Nine sites were selected for the effect of shrub invasion on soil carbon and results show that along the gradient from grassland to shrub communities, soil organic carbon (SOC) had less than 5% increase, which was not significant. Large root biomass but not medium or small root biomass was higher in the shrub community than the others. Another nine sites were selected for the effect of cattle grazing on soil carbon. Grazing did not significantly affect SOC and root biomass, even though it SOC tended to be lower at the grazed sites than the ungrazed. For all 18 sites studied, SOC was the most important carbon pool and was higher than the combination of above- and below ground biomass. Soil carbon was controlled more by soil texture than by

shrub cover or grazing with loamy soils having greater SOC fluxes from native grasslands are relative small. Changes in vegetation from grassland to shrubland increased above-ground biomass but not SOC and grazing did not significantly alter soil carbon. Therefore, current management practices aiming at sustainability and integrity of grassland ecosystems should be maintained. Overall, the Mixedgrass Prairie of Saskatchewan likely contributes very little to total GHG emissions from the agriculture sector. Properly managed, the Mixedgrass Prairie has a well-balanced nutrient cycle that includes various GHGs. The grassland ecosystem plays a role in mitigating climate change by retaining carbon that would be released to the atmosphere with poor grazing management or the conversion to arable agriculture. Government agencies and the ranching industries could best mitigate GHG emissions of Mixedgrass Prairie in Saskatchewan by promoting the retention of above-ground plant material and the avoidance of conversion to cropland.

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## Introduction

GHG sources and sinks in grasslands are less known compared to other ecosystems (IPCC 1992, Tiessen et al. 1998), partly due to the large spatial and temporal variation in the herbaceous cover. In the cropping systems of Saskatchewan, $CO_2$ fluxes were lower under no-till than conventional tillage (Curtin et al. 2000). GHG emissions vary among landscape elements, e.g., $N_2O$ fluxes were higher on footslope than shoulder positions across forest, pasture and cropland in central Saskatchewan (Corre et al. 1996). Soil water content was the most dominant factor controlling denitrification activity, and the intensity of denitrification was largely controlled by the hydrological processes (Van Kessel, et al. 1993, MacKenzie et al. 1997), which reflect topographic influences (Van Kessel, et al. 1993). Spatial variability in GHG emissions is generally high (Topp and Pattey 1997) and a small change in water table may change the sources and sinks relationships in wetlands (Roulet et al. 1993). Therefore, landscape analysis should be incorporated into the modeling of GHG sources and sinks (Pennock et al. 1992).

To date, the focus on GHG sources and sinks in rangelands has been on emissions from livestock. No studies, to the best of our knowledge, have been conducted on the spatial variation of GHG emissions in rangelands, on the modeling of spatial and temporal variation in GHG emission in rangelands with GIS, or linking variability in GHG emissions to biodiversity and productivity of rangelands. Compared to wetlands or temperate/tropical forests, undisturbed shrub-steppe contributes little to global $N_2O$ atmospheric contributions (Mummey et al. 1997). However, spatial variation in GHG emissions in Saskatchewan rangelands may be higher than croplands due to factors such as topographic variation in the rolling plains, changes in vegetation among landscape elements, selective, patch-grazing by cattle. Grazing by cattle reduces the relative abundance of grasses but enhance that of forbs; moderate grazing supports the highest plant species diversity (Bai et al. 2001). Grazing by cattle modifies not only the herbaceous cover of grasslands, but also the amount of viable seeds in the soil seed bank, which determines the potential herbaceous cover after disturbances (Romo and Bai 2003). The spatial and temporal variation in herbaceous cover of rangelands may result in variable N and C cycling rates (Mummey et al. 1997) and contribute to the landscape level variation in GHG emissions. We hypothesize that landscape-level variation in GHG emissions is affected the interaction of landscape elements, cattle grazing and vegetation. Plant species composition, diversity and productivity may be correlated to GHG sources and sinks at landscape levels and the effect of cattle grazing on GHG emissions varies with landscape elements. Results from this project will help improve the accuracy of Canadian GHG inventory for the prairie regions and provide baseline data for landscape level management of rangeland for the reduction of GHG emissions and for optimal ecological and economic returns.

## Project Objectives

1) To contrast the spatial variability in GHG emissions between protected and defoliated rangelands in Saskatchewan, 2) To model landscape-level variations in GHG emissions and to correlate GHG with landscape elements, biophysical factors, plant species diversity, and forage production, 3) To determine the relationship between range condition and soil carbon as well as the effect of shrub invasion on soil carbon, and 4)To provide baseline data for optimal pasture management to maximize the economic and ecological returns.

# Part I: Spatial and Temporal Variation in Greenhouse Gas Flux as Affected by Mowing on Grasslands of Hummocky Terrain in Saskatchewan

## 1.1 Introduction

Greenhouse gases (GHGs) are an important part of the earth's atmosphere, trapping heat by absorbing and then radiating long-wave radiation (Paltridge and Platt, 1976). Since the industrial age, atmospheric concentrations of GHGs such as carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) have increased beyond normal ranges of variation (Prather et al., 1995) due to the burning of fossil fuels, deforestation and changes in land use (Shallcross et al., 2003). Increased greenhouse gas (GHG) emissions and decreased GHG sinks contribute to global climate change (Prather and Ehhalt, 2001). Over the last 100 years, Northern Hemisphere temperatures have increased, often exceeding historic trends in annual temperatures (Mann and Bradley, 1999). In Saskatchewan, the climate has changed in the past 50 years so that spring now begins earlier and winter arrives later (Cutforth et al., 1999).

Greenhouse gases can be investigated at various scales. Greenhouse gases are climate regulators studied at the global scale and over long periods (Wuebbles and Edmonds, 1991). At the national and provincial scale, the production and consumption of GHGs is the centre of an internationally recognized problem that the Canadian and Saskatchewan governments have agreed to confront (Grubb et al., 1999). At the rangeland ecosystem or landscape level, $N_2O$ emissions are a loss of nutrients while $CO_2$ and $CH_4$ sinks store C (Paul and Clark, 1996). Quantifying production and consumption promotes a better understanding of ecosystem functioning and health (Parton et al., 1988; Smith et al., 1995), in turn enabling the mitigation of GHGs (Desjardins et al., 2001). Topography is defined in this study as a collection of landscape elements. Landscape element and defoliation of rangelands creates landscape scale differences in exposure to solar radiation (Buffo et al., 1972), water relations (Ellis, 1938) and nutrient cycles (Archer and Smeins, 1991; Thurow, 1991). Past landscape scale studies have indicated that variation in environmental and plant community attributes due to landscape element and defoliation influence GHG flux. Plant community structure, function and composition influence GHG emissions by altering nutrient cycling (Hooper and Vitousek, 1997), modifying soil hydrology (Naeth et al., 1991) and hosting different microbial communities (Bolton et al., 1993; Wrage et al., 2001). Defoliation by grazing alters GHG patterns directly through feces and urine input (Vermoesen et al., 1997; Yamulki et al., 1998) and indirectly by altering the plant community, which influences the microbial environment and GHG flux (Franzluebbers and Stuedemann, 2003), soil temperature (Ruz-Jerez et al., 1994), and soil water (Thurow, 1991). At the individual soil pedon level, GHG flux is limited by $O_2$, C and N availability (Paul and Clark, 1996). Few studies have attempted to correlate environmental and plant community attributes with biotic processes to develop landscape scale indicators of GHG flux (Bubier and Moore, 1995; Groffman et al., 2000; Mitchell et al., 2003).

The Missouri Coteau is a topographically complex landscape stretching from central Saskatchewan to South Dakota. The defining geological characteristic of the Missouri Coteau is the knob and kettle landscape (Gravenor and Kupsch, 1958). Heterogeneous landscapes such as these provide a variety of microenvironments for organisms that influence GHG flux rates such as grazing vertebrates (Stuth, 1991), soil microbes (Metting, 1993) and plants (Ayyad and Dix, 1964). The flux of GHGs in Saskatchewan rangelands have not been adequately studied, leaving a knowledge gap in the national GHG sources and sinks budget. Study of the flux of GHGs in

Saskatchewan rangelands is likely hampered by the difficulty of designing studies on non-level landscapes and smaller GHG flux rates in rangelands compared to croplands (Bowden, 1986). The objectives of this project were to determine: 1) the spatial variability and 2) magnitude of GHG flux in complex terrain of the Northern Mixedgrass Prairie, and 3) the interaction of landscape element and mowing on GHG flux. Grazing management can then be used on this complex topography as a tool for controlling rangeland GHG flux (Howden et al., 1994), which may help the ranching industry meet obligations outlined by the Kyoto Accord. The null hypotheses were: 1) landscape element and mowing have no effect on environmental attributes, 2) landscape element and mowing have no effect on plant community characteristics, 3) landscape element and mowing have no effect on greenhouse gas flux and 4) environmental attributes, plant community characteristics and GHG flux are not correlated.

## 1.2 Materials and Methods

### 1.2.1 Site description

The study site is approximately 20 km south of Macrorie, SK in the Mixed Grassland Ecoregion (Acton et al., 1998) of the Missouri Coteau. The legal land description is SW-20-26-9W3 (51°14'N, 107°15'W). The Calcareous Dark Brown and Orthic Regosol soils from this area originate from glacial till and are part of the Weyburn Soil Association (Ellis et al., 1970). The topography is hummocky with strongly sloping to moderately rolling surfaces and slopes of 10 to 15% (Ellis et al., 1970). Similar to Coupland's (1950) description of the Mixedgrass Prairie, dominant plant species at the study site are northern wheatgrass and western porcupine grass. Plains rough fescue is present and most abundant in the more protected, mesic areas (Coupland, 1961). Aspen and *Salix* spp. (willow) are common around depressions while *Symphoricarpos occidentalis* Hook. (snowberry) patches occur in mesic landscape positions (Coupland, 1950). The site has not been grazed for at least 10 years before the study, but some depressions have been hayed in the past decade (Ron Dunning, personal communication).

### 1.2.2 Experimental Design and Treatment Design

A landscape scale comparative mensurative experimental design was used to select blocks with the same topographical features (Eberhardt and Thomas, 1991; Pennock, 2004). There were five replicates of six different landscape elements with two treatments imposed as randomized complete blocks on each landscape element for a total of 60 experimental units. The six landscape elements were north-facing aspect, and concave shaped slope (NV), north-facing aspect, and convex shaped slope (NX), south-facing aspect, and concave shaped slope (SV), south-facing aspect, and convex shaped slope (SX), level upland (UP) and depression (DP). Landscape elements were chosen visually and confirmed with digital elevation maps. Mowing is an established simulation of grazing that has been used to test the effects of above-ground biomass removal on the structure, function and composition of range ecosystems without increasing bulk density, selectively removing species or adding urea and feces (Haferkamp and Karl, 1999; Eneboe et al., 2002). The control and mowing treatments were randomly assigned within each replicate. Each treatment plot measured 2 × 20 m with a 2 × 4 m sampling area established at the centre for gas, soil and vegetation sampling. A Jari sickle bar mower (Year-A-Round Corporation, Mankato, MN, USA) was used to cut vegetation to a height of 7.5 cm within the 2 × 20 m treatment plot. Mowing was completed on 18 April 2003 and mowed plant materials were removed from the plots. This experiment was repeated in 2004 on the same landscape elements with mowing imposed on 22 April 2004 on previously unmowed plots. The 2003-2004 sampling season was from 30 April 2003 to 20 April 2004, while the 2004-2005 sampling season was from 3 May 2004 to 10 March 2005.

### 1.2.3 Data collection

#### *1.2.3.1 Environmental attributes*

Selected points within the study area were catalogued with a global position system (GPS; TSC1 Asset Surveyor, Trimble Navigation Limited, Sunnyvale, CA, USA) and a laser-sited theodolite (Electronic Total Station, SET5, Sokkisha Co. LTD., Tokyo, Japan). Two horizontal coordinates were combined with the relative elevation to capture changes in topography within and around the blocks. The three coordinates were used to generate a digital Elevation Model (DEM) with Surfer (Surfer 7, Golden Software, Inc., Golden, CO, USA).

Soil temperature probes (Campbell Scientific 107B; Campbell Scientific Canada, Edmonton, AB) were buried to a depth of 5 cm within each 2 × 4 m sampling area in the spring of 2003. Hourly temperatures were recorded using two Campbell Scientific 21X data loggers. Only one block was monitored because of the distance between landscape elements and a lack of equipment. Temperature probes were removed in the fall of 2003 and reinstalled in the spring of 2004. A Sierra/ISCO model-2501 tipping bucket (Nova Lynx Corporation, Grass Valley, CA, USA) calibrated to 0.658 mm per tip, recorded precipitation on one of the data loggers. Weather data were also obtained from the Rock Point Environment Canada Weather Station located approximately 10 km away (51°9'N107°16'W, Elevation: 725 m) (Environment Canada, 2005a).

Two soil bulk density samples were collected from 0 to 5 cm from each 2 × 4 m sampling area using a 5 × 5 cm metal cylinder (Blake and Hartge, 1984). Surface material was removed before sampling and samples were dried at 80°C for 48 hours and weighed. The average bulk density was reported for each plot.

Five soil samples from 0 to 15 cm from each 2 × 4 m sampling area were collected and bulked for soil texture analysis using the Bouyoucos Hydrometer Procedure (Dodd et al., 2000). Samples were dried at 100°C for 24 hours, sifted and then ground through a 2 mm sieve (Bouyoucos, 1962). Fifty gram samples were saturated with distilled water and subjected to particle dispersal by adding a dispersal agent (0.02N sodium pyrophosphate $Na_4P_2O_7 \cdot 10H_2O$), shaking for 6 hours, resting for 24 hours, blending for 30 seconds and shaking by hand for approximately 30 seconds. Solution density was determined from hydrometer readings 40 seconds and 2 hours after final shaking, respectively. Density readings, corrected for water temperature at time of reading, were used to calculate final percentage of clay, silt and sand.

A snow survey was conducted on 1 March 2004 and 8 March 2005. Snow samples were taken from each 2 × 4 m sampling area using a snow sampling tube (7 cm i.d.). The tube was inserted into the snow pack and the depth of snow was recorded (Goodison et al., 1981). The intact snow core was placed in a labelled plastic bag and weighed. The mass of each snow sample was converted to water equivalent in millimetres of water.

Slope angle and aspect were measured for each plot to calculate potential direct incident radiation (PDIR). The UP and DP landscape elements have no slope angle and therefore no directional aspect. Slope angle and aspect were converted from degrees to radians for PDIR calculations (McCune and Keon, 2002).

Soil samples, from 0 to 15 cm, were collected from all 2 × 4 m sampling areas on each gas sample date. One-half of each sample was used to determine soil water content (oven-dried for 24 hrs at 100°C) (Gardner, 1982). Percentage of water filled pore space (WFPS) from 0 to 15 cm was determined (Peterson and Calvin, 1965) for each 2 × 4 m sampling area from gravimetric soil water, bulk density and particle density. The remaining one-half of each soil sample was frozen and one sample date from spring, summer, and fall of each year were selected for $NH_4^+$ and $NO_3^-$ analysis. Soil samples used to determine N were dried, sifted and ground through a 2 mm sieve. Nitrogen was extracted from the soil using a 2 molar solution of potassium chloride. This solution was refrigerated at 4°C until it was analysed with a colorimetric analyser (Keeney and Nelson, 1982).

#### *1.2.3.2 Plant community structure, species composition and biomass production*

Four, 0.25 $m^2$ quadrats were randomly placed within each 2 × 4 m sampling area in early August of 2003 and 2004. The percentage covers of litter, bare soil, *Selaginella densa* Rydb. (club moss) and each vascular species were visually estimated.

Four, 0.25 $m^2$ quadrats were randomly placed within each plot and all standing crop was hand-clipped to ground level in mid-August of 2003 and 2004. Samples were sorted into wheatgrasses (western wheatgrass, northern wheatgrass and *E. trachycaulus* (Link) Gould ex Shinners (slender wheatgrass)), needle grasses (western porcupine grass, needle-and-thread and *Nassella viridula* (Trin.) Barkworth (green needle grass)), plains rough fescue, other graminoids and forbs (including shrubs and tree seedlings). Samples were dried for 48 hrs at 80°C for a dry weight measurement.

In 2003, a representative portion of each grass and graminoid sample was sorted by colour (green = standing live and brown = standing dead) to determine the live and dead proportions of the entire sample. Samples of 10 g or less were sorted entirely. For samples between 10 and 100 g, 10 g were sorted. Approximately 10% to a maximum of 20 g was sorted for samples over 100 g. The double sample method was used to estimate standing live verses standing dead biomass in 2004 (Pieper, 1978; Anonymous, 1986). Each sample was weighed and the percentage standing live biomass of the total was estimated. Representative portions (as in 2003) of 8 randomly selected samples from each species and mowing treatment were sorted to determine actual percentage of standing live biomass. Regression analysis of the actual live and estimated live percentage was used to calculate actual standing live biomass for all samples.

#### *1.2.3.3 Gas sample collection and analysis*

Immediately following mowing in 2003 and 2004, a chamber base (50 × 50 cm angled aluminium) was inserted in the soil to a depth of 5 cm (Clayton et al., 1994) at the centre of each 2 × 4 m sampling area. Closed clear polymethylmethacrylate sheet (Plexiglas®; Arkema, Paris) chambers, as defined by Hutchinson and Mosier (1981), were built following current guidelines (International Atomic Energy Agency, 1992; P. Rochette and G.L. Hutchinson, unpublished report). Chambers were built 55 × 55 × 20 cm with a closed-cell foam gasket base (Blackmer and Bremner, 1980), an internal, horizontally mounted battery operated fan (Norman et al., 1997) and a 10 cm × 3 mm (i.d.) pressure vent tube covered with open-celled foam to shield it from the wind and prevent mass flow out of the chamber (Conen and Smith, 1998; Hutchinson and Livingston, 2001). Chambers were covered with reflective insulation to prevent temperature increase (Black and Bremner, 1980). A thermocouple wire and a rubber-stopped septum were installed.

Gas samples were collected at approximately 10-day intervals for a total of 18 sample dates from late April to late October in 2003, 17 sample dates from late March to early October in 2004 and 1 sample date in March 2005. A sampling order of plots was randomly generated for each date. Chambers were placed on top of the chamber bases and secured with straps. Gas samples were drawn from chambers using a 20 $cm^3$ syringe at 0 (T0), 30 (T30), and 60 (T60) minutes after chamber placement. The chamber's internal fan was run for 30 seconds before T30 and T60 gas sampling. Samples were stored in labelled, evacuated 12 $cm^3$ vials at 4°C until analysis. Chamber temperatures were recorded at the same intervals. Ambient air samples were taken at chamber height throughout the sampling period and across the site. When a base was obstructed by snow during spring sampling, chambers were placed on top of snow.

Gas samples were analysed for $CO_2$, $N_2O$, and $CH_4$ using gas chromatography (GC) (Farrell et al., 2002). Sample analyses were performed either at the Department of Soil Science, University of Saskatchewan, Saskatoon or the Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada, Swift Current. Although the two labs used slightly different GC systems, previous work has demonstrated that they produced comparable results (R.E. Farrell, personal communication).

Carbon dioxide analyses at Saskatoon, SK were conducted using a Varian CP-2003 micro-GC (Varian Canada Inc., Mississauga, ON) equipped with a micro-thermal conductivity detector (TCD) and a Poraplot U column (10.0 m × 0.32 mm i.d. silica capillary column), both maintained at 44°C. Gas samples were introduced using a 30-position, vacuum-activated valve system with injection temperature of 110°C, sample volume of 50 µL and ultra-high purity helium (UHP He) as the carrier gas. The system was calibrated using standard gases ($CO_2$ in air) obtained from Praxair (Mississauga, ON). Data was processed with Varian *Star Chromatography Workstation* software (ver. 5.51). Internal calibration curves were obtained by applying linear, least squares regression to the $CO_2$ concentration (ppmV) versus peak area data. Carbon dioxide concentrations in the headspace samples were then calculated automatically from the regression equation.

Methane and $N_2O$ analyses were carried out sequentially using a Varian CP 3800 GC (Varian Canada Inc., Mississauga, ON) equipped with a flame ionization detector (FID) for $CH_4$ analyses and dual electron capture detectors (ECD) for $N_2O$ analyses. For $CH_4$ analyses, the injector temperature was 70°C, the column temperature was 35°C and detector temperature was 200°C. Separations were carried out using a Cpsil 5 CB column (15.0 m × 0.25 mm i.d. fused silica capillary column, DF = 0.25 µm) with UHP He (15 mL $min^{-1}$) as the carrier gas. Samples of 2.5 mL were introduced using a CombiPAL™ auto-sampler (CTC Analytics AG, Switzerland) with on-column injection and a split ratio of 3:1. The system was calibrated using standard gases ($CH_4$ in air) obtained from Praxair.

The $N_2O$ system was analysed with injector temperature at 100°C, column temperature at 35°C and detector temperature at 370°C. Separations were carried out using Poraplot Q columns (12.5-m × 0.32-mm i.d. fused silica capillary column, including a 2.5-m particle trap, DF = 8 µm) with UHP He (16 mL $min^{-1}$) as the carrier gas and P5 (95:5 Ar:$CH_4$ mix) as the make-up gas (11 mL $min^{-1}$). The auto-sampler injects 2.5 ml of gas sample on-column using a split injection system with a split ratio of 10:1 and P5 as the make-up gas and UHP He as the carrier gas. The system was calibrated using standard gases ($N_2O$ in $N_2$) obtained from Praxair.

Data for the $CH_4$ and $N_2O$ analyses was processed with Varian *Star Chromatography Workstation* software (ver. 6.2). Internal calibration curves were obtained by applying linear, least squares regression to the gas concentration (ppmV $CH_4$; ppbV $N_2O$) versus peak area data. Methane and $N_2O$ concentrations in the headspace samples were then calculated automatically from the regression equations.

At Swift Current, SK the concentrations of all three gases were determined using a Varian CP 3800 equipped with a CombiPAL™ auto-sampler. The auto-sampler injects the gas sample into a 10 port sampling valve, which then transfers the sample to 2, 0.5 mL sample loops. One loop introduces the sample onto an 80/100 mesh Porapak N pre-column (0.4572 m × 3.18 mm i.d.; injector temperature = 70°C) and the other introduces the sample onto an 80/100 mesh Porapak QS column (1.83 m × 3.18 mm i.d.; column temperature = 80°C) using UHP He as the carrier gas. Carbon dioxide is then determined using a TCD maintained at 130°C with a filament temperature of 220°C and $CH_4$ is determined using a FID maintained at 200°C. For $N_2O$ analyses, the sample was introduced onto an 80/100 mesh Hayesep D column (1.83 m × 3.18 mm i.d.) using P10 (90:10 Ar:$CH_4$ mix, flow rate = 30 mL $min^{-1}$) and detected using a $^{63}$Ni-ECD maintained at 380°C.

Peak areas were quantified by comparing sample peak areas with that of a commercial custom mixed standard (Praxair) composed of $CO_2$ 385 $\mu L\ L^{-1}$ (balance $N_2$), $CH_4$ 1.46 $\mu L\ L^{-1}$ and $N_2O$ 1.11 $\mu L\ L^{-1}$. Peak areas for all three gases were quantified with Varian *Star Chromatography Workstation* software (ver. 6.2).

Sample concentrations were examined for outliers, which were replaced with averages for each time interval. Minimum detectable concentration difference (MDCD) for a given sample date was calculated as two times the standard deviation of checked ambient samples for that sample date. Sample concentrations were adjusted for air temperature and atmospheric pressure. Chamber volume, chamber area and MDCD were used to determine flux rate. Differences between T60 and T30 samples, T30 and T0 samples and T60 and T0 samples were compared to MDCD. Differences less than the MDCD scored "FALSE" and those flux rates equalled zero. The least squares method was used to compare sample time intervals with adjusted sample concentrations from one experimental unit. The generated slope equalled the mass of a GHG released or consumed $m^{-2}\ s^{-1}$. Carbon dioxide flux rates were converted from µg $CO_2\ m^{-2}\ s^{-1}$ to kg of $CO_2$-C $ha^{-1}\ d^{-1}$, $CH_4$ flux rates were converted from ng $CH_4\ m^{-2}\ s^{-1}$ to g $CH_4$-C $ha^{-1}\ d^{-1}$ and $N_2O$ flux rates were converted from ng $N_2O\ m^{-2}\ s^{-1}$ to g $N_2O$-N $ha^{-1}\ d^{-1}$ to calculate cumulative flux rates. Each new flux rate was multiplied by the number of days out of the sampling season that each individual sample date represented to arrive at cumulative emission or consumption values. Weighted daily average values were calculated by dividing the cumulative emission or consumption values of each 2 × 4 m sampling area by the number of days that sample season covered.

### 1.2.4 Data analysis

General linear model (PROC GLM) from SAS (SAS Institute Inc., Cary, NC, USA) was used to analysis variance to determine the effects of landscape element, mowing and sample date on GHG flux rates and WFPS. The effects of landscape element and mowing on different measured factors including soil physical characteristics, soil temperature, snow accumulation, biomass (standing-live graminoid, standing-dead graminoid, forbs and shrubs and total above-ground biomass), species richness, species evenness and Shannon-Weiner diversity index were determined from an ANOVA generated with PROC GLM. Mean separation was done using least significant difference test (LSD). A significant level of P = 0.05 was used.

The relationship between landscape element, mowing and species composition was plotted using Detrended Correspondence Analysis (DCA) in CANOCO (ver. 4.5) (Microcomputer Power, Ithaca, NY, USA) (ter Braak and Šmilauer, 2002). Detrended Canonical

Correspondence Analysis (DCCA) from CANOCO was used to determine the standard deviation of the species gradients for each year (6.131, 2.304, 2.370 and 1.661 for Axes 1 to 4 in 2004 and 5.076, 2.160, 1.946, 1.390 for Axes 1 to 4 in 2003). Axis 1 had a standard deviation greater than 3 to 4, indicating a unimodal species response most appropriately analysed with Canonical Correspondence Analysis (CCA) from CANOCO using Hill's technique to scale species response (ter Braak, 1987; ter Braak and Šmilauer, 2002). This technique plots experimental units and environmental gradients using points and arrows, respectively, to generate a joint plot that can only be interpreted relatively (ter Braak, 1987; McCune and Grace, 2002). Canonical Correspondence Analysis uses multiple linear least-squares regression to determine weighted average experimental unit scores (Palmer, 1993). The joint plot is plotted using Linear Combination (LC) scores of dependant and independent variables. Canonical Correspondence Analysis shows how environmental gradients like soil water control species distribution and how environmental gradients like $CO_2$, $CH_4$ and $N_2O$ flux change in relation to species composition. Therefore, species composition can be used to distinguish areas with high or low GHG flux (Bubier, 1995; Bubier and Moore, 1995). The length of an environmental variable arrow indicates its relative importance, the direction indicates its correlation with the species composition axis and the angle of one arrow relative to another indicates the relative correlation between the two variables (Palmer, 1993).

Species recorded in less than 5% of experimental units were removed from the CCA matrix to limit the influence of rare species (McCune and Grace, 2002). Correlated variables that contained similar information were removed to aid clarity. Significance of remaining variables was determined using forward selection. This step-wise selection process uses a Monte Carlo test with 9,999 unrestricted permutations to determine the P value of each environmental variable (ter Braak and Šmilauer, 2002). Variables with a $P > 0.01$ were removed (Qian et al., 2003).

## 1.3 Results

### 1.3.1 Variability in environmental attributes as affected by landscape element and mowing

During the 2003 sampling season, temperatures in the Macrorie area were hotter and precipitation was less than the 30-year average (Table 1.1). The average monthly air temperature at the Rock Point Environment Canada Weather Station in 2003 was equal to or warmer than the 30-year average in every month but February, March and November. The mean annual temperature in 2003 was 0.5°C higher than the 30-year average. Total monthly precipitation during winter and early spring was mostly higher in 2003 than the 30-year average, but precipitation for the whole year was 71% of the 30-year average.

Temperature during the 2004 sampling season was lower than the 30-year average (Table 1.1). From April to October, only April and September were warmer than the 30-year average. The mean annual temperature was 0.1°C warmer in 2004 than the 30-year average. Precipitation from April through October in 2004 was 120% of the 30-year average for the same period. Over the entire year, 2004 precipitation was 106% of the 30-year average.

Mowing in the previous year did not influence 2004 snow accumulation (displayed as mm snow water equivalent) but landscape element did influence 2004 snow accumulation ($P < 0.001$) (Figure 1.1). Snow water equivalent was greatest on the DP landscape element, the NV landscape element had the second greatest and all other landscape elements had less accumulated snow water equivalent. There was no snow accumulation on the site on the snow sampling date in the spring of 2005, but water had accumulated in the depression landscape element at that time (personal observation).

**Table 1.1** Mean monthly air temperatures (°C) and total monthly precipitation (mm) at Rock Point, SK.

| Month | ----- 30-Year Average ----- | | ---------- 2003 ---------- | | ---------- 2004 ---------- | |
|---|---|---|---|---|---|---|
| | Temperature | Precipitation | Temperature | Precipitation | Temperature | Precipitation |
| January | -14.0 | 17.1 | -12.9 | 21.4 | -15.9 | 10.6 |
| February | -10.4 | 10.3 | -13.6 | 24.8 | -7.5 | 5.0 |
| March | -4.0 | 18.2 | -6.2 | 2.6 | -1.0 | 6.8 |
| April | 4.9 | 22.6 | 5.2 | 52.4 | 6.0 | 8.4 |
| May | 11.5 | 55.1 | 11.6 | 24.2 | 8.3 | 50.6 |
| June | 15.9 | 69.7 | 15.9 | 37.8 | 13.4 | 74.2 |
| July | 18.6 | 60.1 | 20.3 | 33.0 | 18.2 | 59.2 |
| August | 17.8 | 36.5 | 21.8 | 7.4 | 15.1 | 105.8 |
| September | 12.2 | 30.2 | 12.2 | 32.6 | 12.3 | 28.4 |
| October | 5.4 | 18.5 | 8.6 | 21.4 | 4.0 | 24.2 |
| November | -4.8 | 17.9 | -8.6 | 5.6 | -0.6 | 0.6 |
| December | -11.6 | 20.9 | -6.6 | 4.8 | -9.3 | 25.6 |
| Average | 3.5 | | 4.0 | | 3.6 | |
| Total | | 366.9 | | 268.0 | | 399.4 |

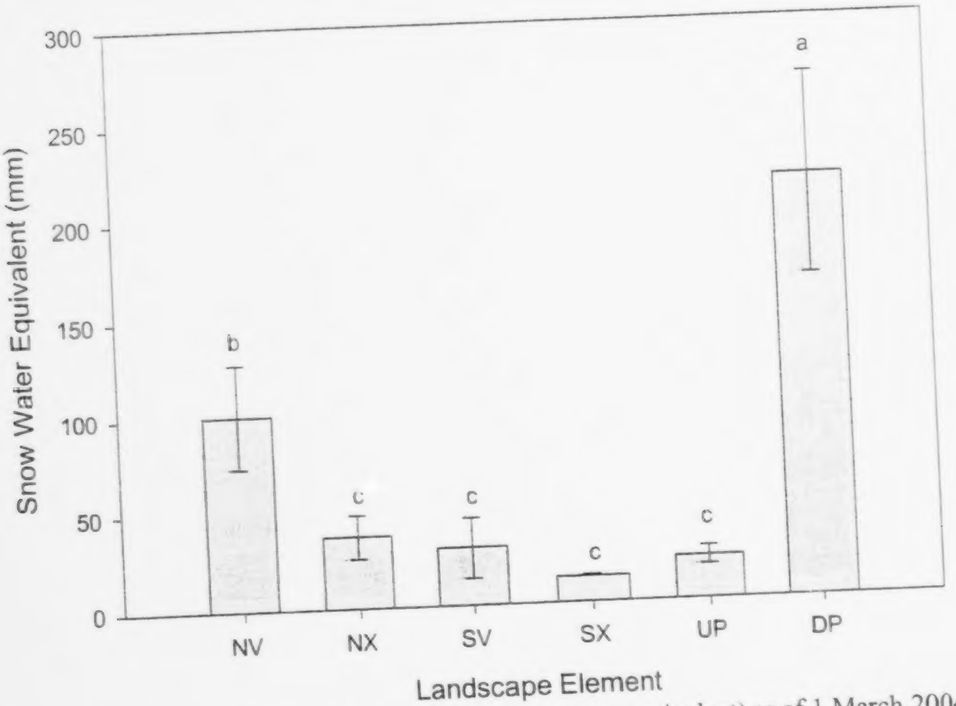

**Figure 1.1** Snow accumulated (mean ± SE, mm water equivalent) as of 1 March 2004 on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements at Macrorie, SK. Bars with the same letters are not significantly different (P = 0.05).

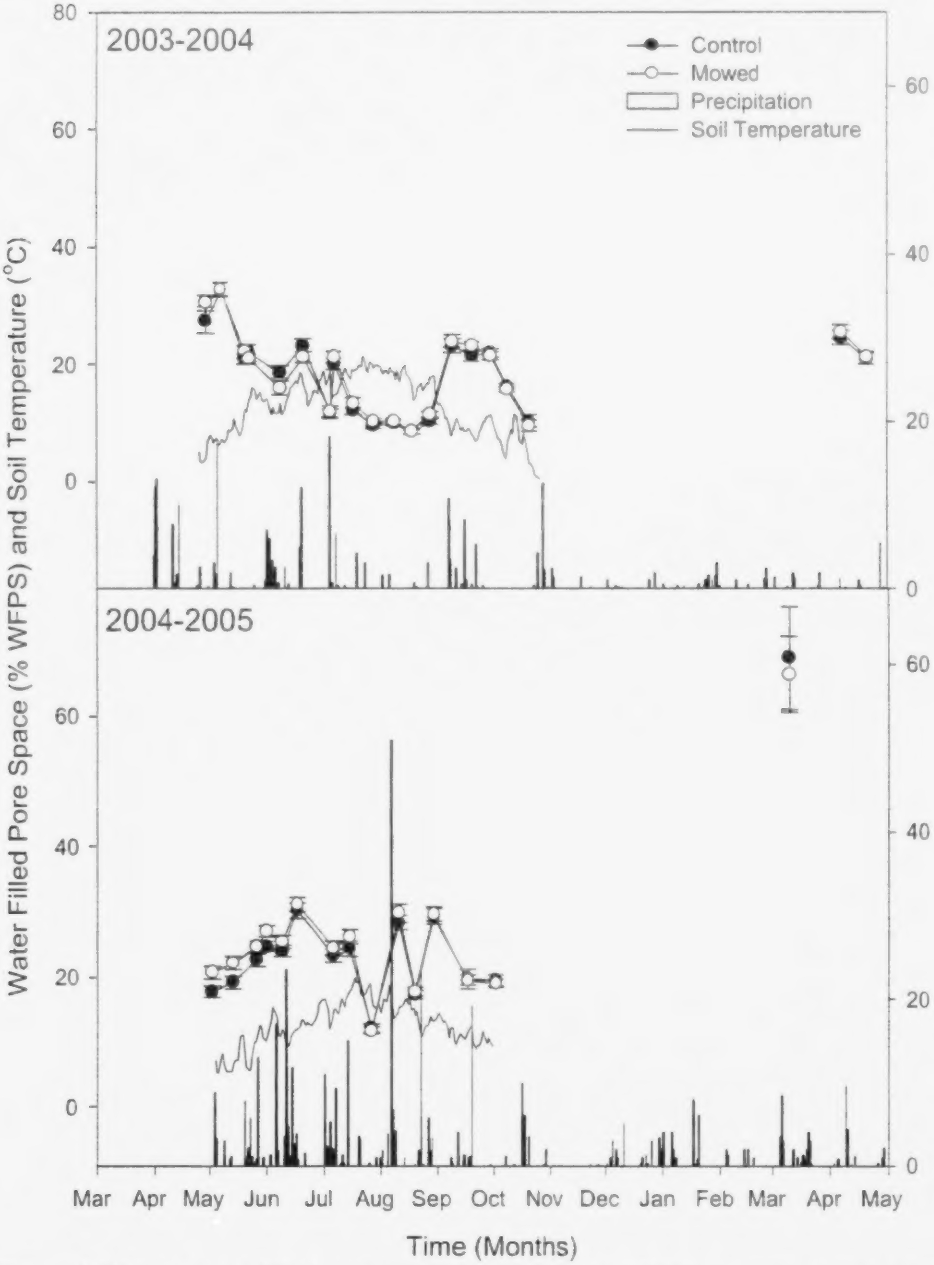

**Figure 1.2** Mean water filled pore space (mean ± SE, % WFPS) for control and April mowing averaged across six landscape elements on sample dates and mean soil temperature (at 5 cm depth, °C) during 2003-2004 and 2004-2005 sampling season. Bars represent precipitation (mm) as recorded at Rock Point, SK.

Soil temperatures peaked in July and August (Figure 1.2). Mowing did not significantly change soil temperature. The difference in soil temperature among landscape elements over the sampling season was as high as 6.4°C in 2003 and 4.6°C in 2004.

When years were considered a random variable, soil temperature was different among landscape elements, but not between mowing treatments (Table 1.2). South-facing landscape elements had the highest soil temperature, north-facing and DP landscape elements had the lowest soil temperatures, and UP landscape elements had intermediate soil temperatures. When surface shape and year were considered random variables, north-facing landscape elements were 4.7°C cooler than south-facing landscape elements, but there was no difference between mowing treatments.

**Table 1.2** Mean soil temperature (mean ± SE, °C) at 5 cm depth on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland, DP – depression landscape elements with control and April mowing over 2003 and 2004 at Macrorie, SK. North and south landscape elements represent combined temperatures from concave and convex shapes of respective north and south-facing aspects.

| Landscape Element | Soil Temperature (°C) |
|---|---|
| NV | 14.4 ± 0.57 c[1] |
| NX | 13.9 ± 0.29 c |
| Combined north-facing landscape elements | 14.2 ± 0.31 B[2] |
| SV | 18.0 ± 0.64 ab |
| SX | 19.8 ± 1.14 a |
| Combined south-facing landscape elements | 18.9 ± 0.69 A |
| UP | 16.0 ± 1.52 bc |
| DP | 13.8 ± 0.57 c |

[1] Means with the same lower case letters are not significantly different (P = 0.05).
[2] Means with the same upper case letters are not significantly different (P = 0.05).

Potential direct incident radiation, derived from aspect and slope (Table 1.3) differed significantly among landscape elements (Figure 1.3). The NV and NX landscape elements receive 91 and 89% less, respectively PDIR than the UP and DP landscape elements. South-facing landscape elements received similar PDIR as the UP landscape element.

**Table 1.3** Aspect (degree, north = 0, east = 90, south = 180, west = 270) and slope (degree) of NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements at Macrorie, SK.

| Landscape Element | Aspect ( ° ) | Slope ( ° ) |
|---|---|---|
| NV | 15 | 8 |
| NX | 270 | 10 |
| SV | 162 | 13 |
| SX | 149 | 14 |
| UP | 0 | 0 |
| DP | 0 | 0 |

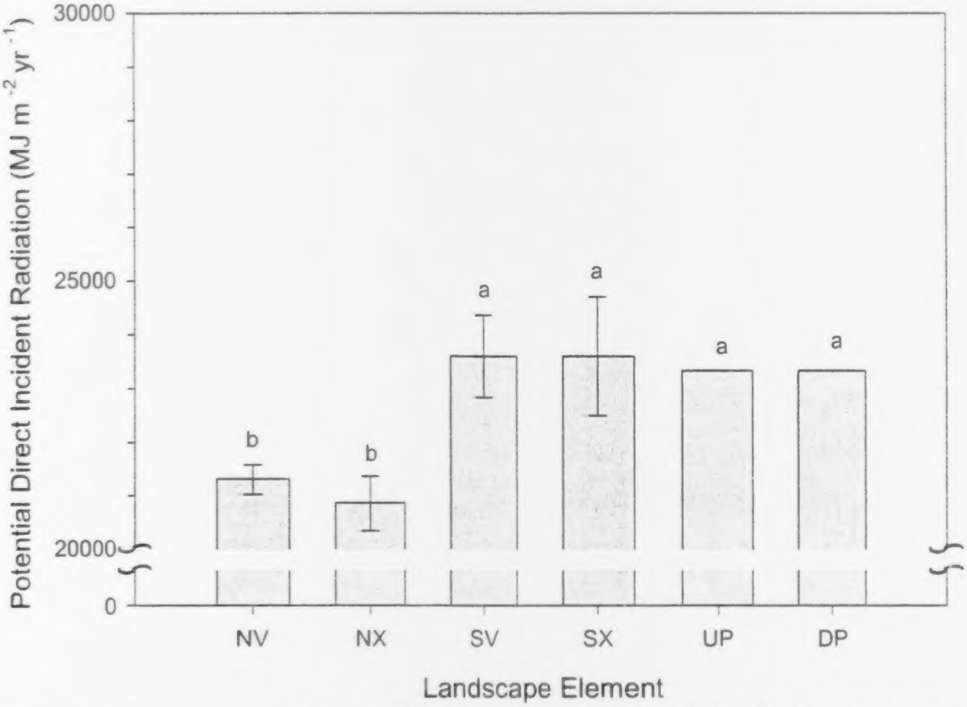

**Figure 1.3** Average annual potential direct incident radiation (MJ $m^{-2}$ $yr^{-1}$) calculated using the longitude, aspect and slope of NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements at Macrorie, SK.

Soils have a sand content between 49 and 53% except soil from the DP landscape element with 36% sand (Table 1.4). Clay content ranges from 9 to 15%. Sand and silt, but not clay, varied among landscape elements. Soils of the DP landscape element have less sand and more silt than soils of other landscape elements. Soils of the north-facing and UP landscape elements have a loam texture while soils of the south-facing landscape elements are a sandy loam texture. Soils of the DP landscape element have the greatest silt and clay content, giving them a silt loam soil texture. Bulk density varied with landscape element and was greatest on the SX landscape element and least the DP landscape element. Bulk density on the SX landscape element is nearly two times greater than on the DP landscape element.

**Table 1.4** Physical characteristics of soil (mean ± SE) of NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements at Macrorie, SK.

| Landscape Element | Sand (%) | Silt (%) | Clay (%) | Soil Texture[1] | Bulk Density[2] ($g\ cm^{-3}$) |
|---|---|---|---|---|---|
| NV | 50 ± 0.8 a[3] | 39 ± 0.9 b | 11 ± 1.0 | Loam | 0.68 ± 0.030 d |
| NX | 51 ± 0.8 a | 38 ± 0.3 b | 11 ± 1.0 | Loam | 0.72 ± 0.011 cd |
| SV | 53 ± 1.0 a | 38 ± 1.1 b | 9 ± 0.7 | Sandy Loam | 0.75 ± 0.024 bc |
| SX | 53 ± 0.9 a | 35 ± 0.6 b | 12 ± 0.7 | Sandy Loam | 0.90 ± 0.024 a |
| UP | 49 ± 1.3 a | 37 ± 0.8 b | 14 ± 1.3 | Loam | 0.81 ± 0.025 b |
| DP | 36 ± 3.0 b | 49 ± 2.6 a | 15 ± 2.4 | Silty Loam | 0.48 ± 0.018 e |

[1] From 0 to 15 cm. Soil texture classes are based on The Canadian System of Soil Classification (Soil Classification Working Group, 1998).

[2] From 0 to 5 cm.

[3] Means with the same letters within a column are not significantly different (P = 0.05).

Water filled pore space (WFPS), an indicator of soil water content and anaerobic conditions, appeared to change with precipitation events and soil temperature (Figure 1.2). Average WFPS for all landscape elements and mowing treatments at the beginning of the sampling season was 29% and 19% for 2003-2004 and 2004-2005, respectively. A 10 to 15% fluctuation in WFPS between dry and wet periods was common. The highest average WFPS was reached in May 2003 (33%) and March 2005 (68%) and the lowest in August 2003 (9%) and July 2004 (12%). In the fall average WFPS was 10% for 2003-2004 and 19% for 2004-2005.

Water filled pore space was interactively affected by landscape element and sample date, mowing and sample date, and mowing and landscape element in 2003 (Table 1.5). In 2004, WFPS was interactively affected by landscape element and sample date, and by mowing and landscape element.

**Table 1.5** Water filled pore space (mean ± SE, % WFPS) for NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements with control and April mowing in 2003-2004 and 2004-2005 at Macrorie, SK.

| Landscape Element | 2003-2004 | | | 2004-2005 | | |
|---|---|---|---|---|---|---|
| | Control | Mowing | Mean | Control | Mowing | Mean |
| NV | 19.1 ± 0.86 A[1] | 18.6 ± 0.79 A | 18.9 ± 0.58 | 30.5 ± 3.24 | 26.2 ± 1.91 | 28.3 ± 1.89 |
| NX | 17.5 ± 0.71 A | 16.8 ± 0.69 A | 17.1 ± 0.49 | 25.5 ± 1.98 B | 30.8 ± 2.45 A | 28.2 ± 1.59 |
| SV | 16.9 ± 0.79 A | 16.9 ± 0.82 A | 16.9 ± 0.57 | 22.1 ± 1.10 B | 24.2 ± 1.15 A | 23.2 ± 0.80 |
| SX | 18.0 ± 0.85 A | 16.8 ± 0.74 B | 17.4 ± 0.56 | 24.3 ± 1.04 A | 25.0 ± 1.03 A | 24.6 ± 0.73 |
| UP | 17.4 ± 0.81 [2] | 21.2 ± 0.96 | 19.3 ± 0.64 | 24.0 ± 1.39 A | 24.9 ± 1.57 A | 24.4 ± 1.05 |
| DP | 17.1 ± 0.96 B | 19.0 ± 0.97 A | 18.1 ± 0.69 | 23.4 ± 0.91 A | 24.5 ± 0.91 A | 23.9 ± 0.64 |
| Mean | 17.7 ± 0.34 | 18.2 ± 0.34 | | 25.0 ± 0.75 | 25.9 ± 0.66 | |

[1] Means followed by the same upper case letter within a row and a sampling season are not significantly different (P = 0.05).

[2] Treatment means with no letter showed interaction between mowing and sample date.

Within each landscape element in 2003-2004, mowing decreased WFPS on the SX landscape element (P = 0.003; Table 1.5), increased WFPS on the DP landscape element (P = 0.001) and caused no change on all other landscape elements (P > 0.05). Water filled pore space on the UP landscape element was influenced by the interaction of mowing and sample date (P = 0.001). Mowing increased WFPS on 30 April, 23 May and 29 July and had no effect on WFPS on all other sample dates. The DP landscape element, because of flooding, was not mowed until 26 June 2003. When the DP control and mowing treatments were sampled, mowing increased WFPS (P < 0.001).

Within landscape element during the 2004-2005 sampling season, mowing increased WFPS compared to control on the NX and SX landscape elements (P = 0.001 and 0.003, respectively). Water filled pore space was interactively influenced by mowing and sample date on the NV landscape element (P = 0.002). Mowing increased WFPS compared to control on 3 May, 27 May and 1 June for the NV landscape element. For all other sample dates, WFPS was not different between mowing and control. There was no significant difference between treatments in SX, UP and DP landscape elements.

Differences in WFPS among landscape elements depended on sample date in both years (Figure 1.2). On 21 May 2003, WFPS was greatest on the NV, UP and NX landscape elements (P = 0.039). On 23 May 2003, WFPS was greatest on the DP landscape element (P < 0.001). On 5 July 2003, WFPS was greatest on the DP landscape element and least on the SV landscape element (P < 0.001). On 18 July 2003, mowing and landscape element interactively influenced WFPS (P = 0.010). Except for the DP landscape element where mowing increased WFPS compared to control, mowing did not influence WFPS on any landscape elements. For the three sample dates between 29 July 2003 and 19 August 2003, WFPS was greatest on the DP landscape element, followed by NV, NX, UP, SX, and SV landscape elements (P < 0.001 for all three dates). On 10 September 2003, WFPS was greatest on the UP, SX and SV landscape elements (P = 0.017).

In 2004-2005, mowing increased WFPS compared to control between 3 May 2004 and 6 June 2004 (P < 0.05), but WFPS was not different between mowing treatments on other dates (P

$> 0.05$). Except on 6 July 2004 when WFPS was greatest on the SX landscape element, WFPS was greatest on the DP, NV, NX and sometimes the UP landscape elements.

Soil $NO_3^-$ varied among the three sample dates and landscape elements in 2003, but not among mowing treatments (Figure 1.4). Soils sampled on 30 April had the most $NO_3^-$, 9 September soil samples had 44% less than 30 April soil samples and soil samples from 5 July had 85% less than those from 30 April. Soils from UP and NV landscape elements had more $NO_3^-$ than soils from all other landscape elements.

In 2004, landscape element and sample date influenced soil $NO_3^-$ (both at $P < 0.001$), but not mowing (Figure 1.4). Soil samples from 6 July had the most $NO_3^-$ while soils sampled on 3 May had 34% less than those on 6 July and soils sampled on 19 September had 45% less than those on 6 July. The soils on the DP landscape element had the most $NO_3^-$, the NV, NX, SV and SX landscape elements soils had the least $NO_3^-$, and UP soils had intermediate amounts of $NO_3^-$.

Soil $NH_4^+$ was similar among the three sample dates in 2003 (Figure 1.5). Overall, $NH_4^+$ varied significantly among the soils of landscape elements, decreasing from the DP, NX, UP, NV, SV to SX ($P = 0.045$). Mowing did not change $NH_4^+$ of soils. Overall soil $NH_4^+$ in 2004 was affected by sample date and landscape element, but not by mowing. The 3 May soil samples had the most $NH_4^+$ while soil samples from 6 July had 40% less $NH_4^+$ than those from 3 May and soil samples from 19 September had 57% less $NH_4^+$ than those from 3 May ($P < 0.001$). Ammonium was greater in NV, DP and NX than other landscape elements ($P = 0.002$).

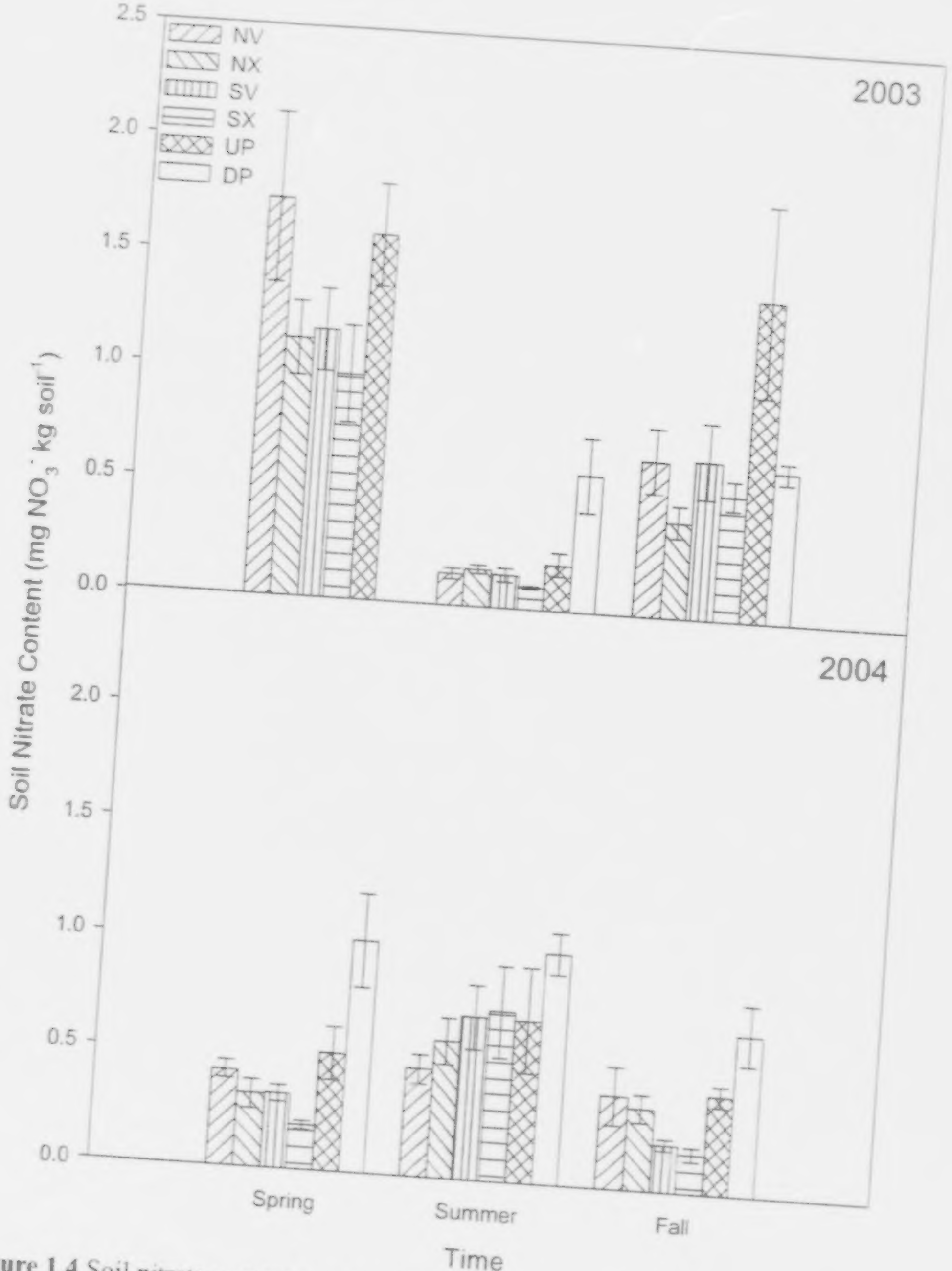

**Figure 1.4** Soil nitrate content (mean ± SE, mg $NO_3^-$ kg $soil^{-1}$, 0-15 cm) on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements during 2003 and 2004 at Macrorie, SK (Spring = 30 April 2003 and 3 May 2004, Summer = 5 July 2003 and 6 July 2004, Fall = 9 September 2003 and 19 September 2004).

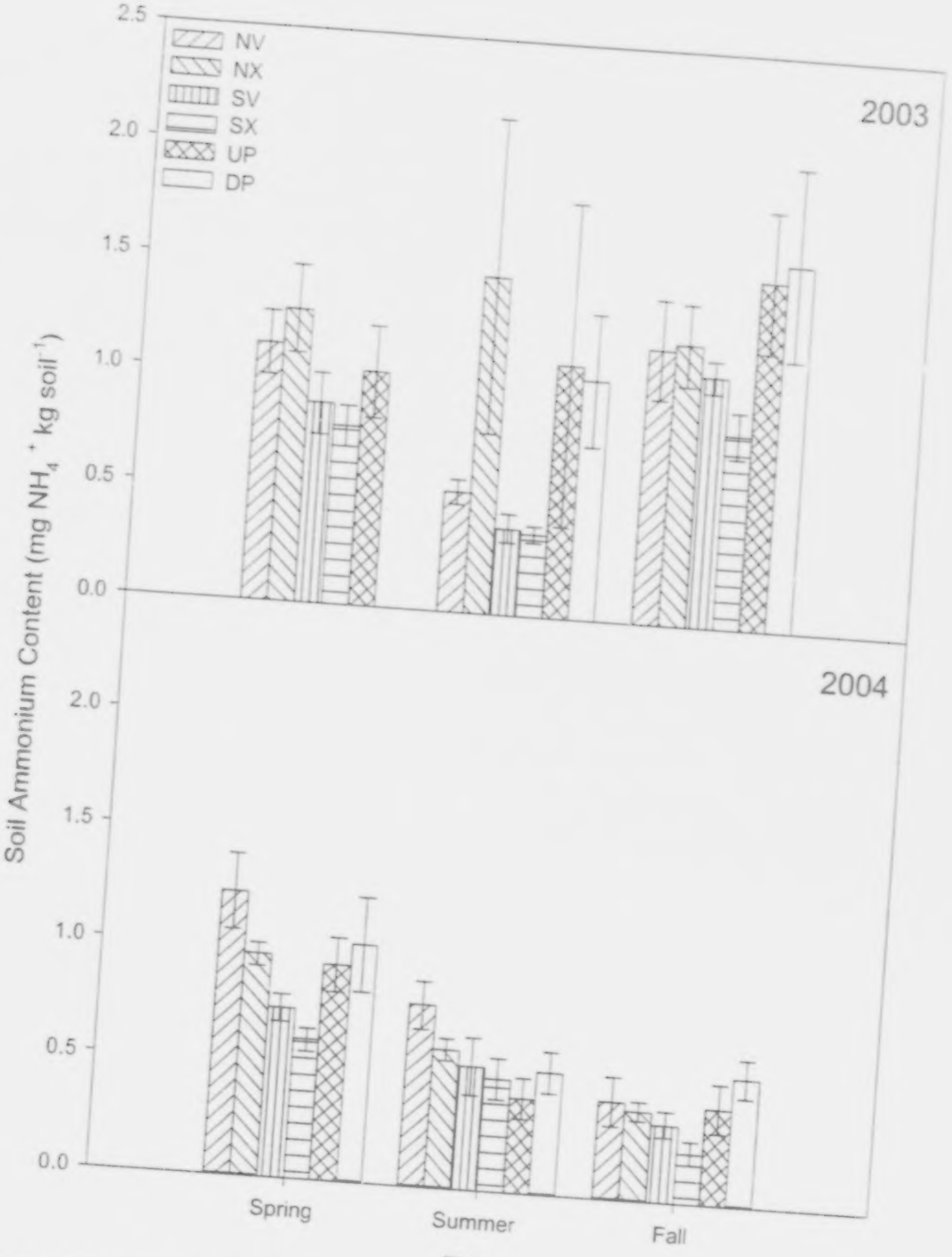

**Figure 1.5** Soil ammonium content (mean ± SE, mg $NH_4^+$ kg $soil^{-1}$, 0-15 cm) NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements during 2003 and 2004 at Macrorie, SK (Spring = 30 April 2003 and 3 May 2004, Summer = 5 July 2003 and 6 July 2004, Fall = 9 September 2003 and 19 September 2004).

### 1.3.2 Variability in plant community characteristics and biomass production as affected by landscape element and mowing

Species richness was lower on the UP landscape element than other landscape elements in both years ($P = 0.010$ for 2003 and $P = 0.015$ for 2004), but was similar between mowing treatments ($P > 0.05$), averaging 11 and 13 species per $m^2$ for 2003 and 2004, respectively (Table 1.6). Species evenness was greatest on the UP and DP landscape elements, least on NX and NV, and intermediate on SX and SV landscape elements in 2003 ($P < 0.001$). In 2004, species evenness was greatest on SX, SV, DP and UP and least on NX and NV landscape elements ($P < 0.001$). Mowing increased species evenness in 2004, but not in 2003.

The Shannon-Wiener Diversity Index (H') differed significantly among landscape elements in 2003 ($P < 0.001$) (Table 1.6). Diversity was greatest on the DP and SX landscape elements and lowest on SV, NX and NV landscape elements. The diversity index in 2004 was greatest on the SX and least on NV landscape elements ($P = 0.003$). Mowing had no affect on the diversity index in either year ($P > 0.05$).

Detrended Correspondence Analysis (DCA) based on species composition produced similar separation of experimental units for both years (Figures 1.6 and 1.7). The DP landscape element was separated from other landscape elements along Axis 1. North-facing landscape elements were separated from south-facing landscape elements along Axis 2 while the UP landscape element overlapped with south-facing and north-facing landscape elements. Except for variation in species composition among SX landscape elements in 2004, which were closely grouped, variation within the north-facing landscape elements tended to be less than in other landscape elements. One NX and one NV experimental unit in 2003 and 2004, respectively, were not included in the grouping because they appeared to be outliers.

**Table 1.6** Plant community characteristics (mean ± SE) per 0.25 $m^2$ (mean of 4, 0.25 $m^2$ quadrats) in August of 2003 and 2004 on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements with control and April mowing at Macrorie, SK.

| Landscape | ----------- Richness | ----------- | ----------- | --------------- Evenness | --------------- | --------------- | Shannon-Wiener Diversity Index | | |
|---|---|---|---|---|---|---|---|---|---|
| Element | Control | Mowing | Mean | Control | Mowing | Mean | Control | Mowing | Mean |
| | | | | 2003 | | | | | |
| NV | 12 ± 2 | 11 ± 1 | 11.5 a[1,2] | 0.40 ± 0.06 | 0.47 ± 0.05 | 0.44 c | 0.99 ± 0.17 | 1.13 ± 0.15 | 1.06 d |
| NX | 11 ± 1 | 11 ± 2 | 11.2 a | 0.50 ± 0.05 | 0.51 ± 0.06 | 0.50 c | 1.21 ± 0.17 | 1.23 ± 0.22 | 1.22 cd |
| SV | 11 ± 1 | 10 ± 0 | 10.5 a | 0.63 ± 0.08 | 0.63 ± 0.04 | 0.63 b | 1.49 ± 0.20 | 1.49 ± 0.11 | 1.49 b |
| SX | 9 ± 1 | 12 ± 1 | 10.6 a | 0.62 ± 0.05 | 0.76 ± 0.03 | 0.69 ab | 1.36 ± 0.09 | 1.85 ± 0.07 | 1.60 ab |
| UP | 6 ± 1 | 9 ± 1 | 7.5 b | 0.79 ± 0.06 | 0.69 ± 0.04 | 0.74 a | 1.32 ± 0.13 | 1.49 ± 0.17 | 1.41 bc |
| DP | 13 ± 2 | 11 ± 1 | 11.8 a | 0.72 ± 0.05 | 0.74 ± 0.07 | 0.73 a | 1.83 ± 0.20 | 1.73 ± 0.17 | 1.78 a |
| Mean | 10.4 | 10.6 | | 0.61 | 0.64 | | 1.37 | 1.49 | |
| | | | | 2004 | | | | | |
| NV | 13 ± 2 | 13 ± 2 | 13.1 a[2] | 0.52 ± 0.04 | 0.59 ± 0.05 | 0.56 c | 1.31 ± 0.17 | 1.52 ± 0.18 | 1.42 c |
| NX | 13 ± 1 | 15 ± 2 | 14.4 a | 0.60 ± 0.05 | 0.69 ± 0.05 | 0.65 b | 1.55 ± 0.11 | 1.87 ± 0.17 | 1.71 ab |
| SV | 14 ± 1 | 12 ± 1 | 13.1 a | 0.72 ± 0.05 | 0.74 ± 0.04 | 0.73 a | 1.93 ± 0.15 | 1.82 ± 0.18 | 1.87 ab |
| SX | 12 ± 1 | 13 ± 1 | 12.7 a | 0.73 ± 0.03 | 0.80 ± 0.03 | 0.77 a | 1.82 ± 0.08 | 2.07 ± 0.12 | 1.95 a |
| UP | 11 ± 1 | 9 ± 1 | 9.9 b | 0.75 ± 0.03 | 0.73 ± 0.03 | 0.74 a | 1.79 ± 0.08 | 1.58 ± 0.16 | 1.68 b |
| DP | 14 ± 3 | 13 ± 1 | 13.1 a | 0.73 ± 0.04 | 0.76 ± 0.06 | 0.75 a | 1.88 ± 0.19 | 1.92 ± 0.17 | 1.90 ab |
| Mean | 12.9 | 12.5 | | 0.68 B[3] | 0.72 A | | 1.71 | 1.80 | |

[1] When interaction between landscape element and mowing was not significant ($P > 0.05$), means of main effects were separated using LSD. When interaction between landscape element and mowing was significant, data were analysed within each landscape element and each mowing treatment. Means were then separated within each mowing treatment or landscape element using LSD.

[2] Means followed by the same lower case letters within a column and a year are not significantly different ($P = 0.05$).

[3] Means followed by the same upper case letters within a row and a plant community characteristic are not significantly different ($P = 0.05$).

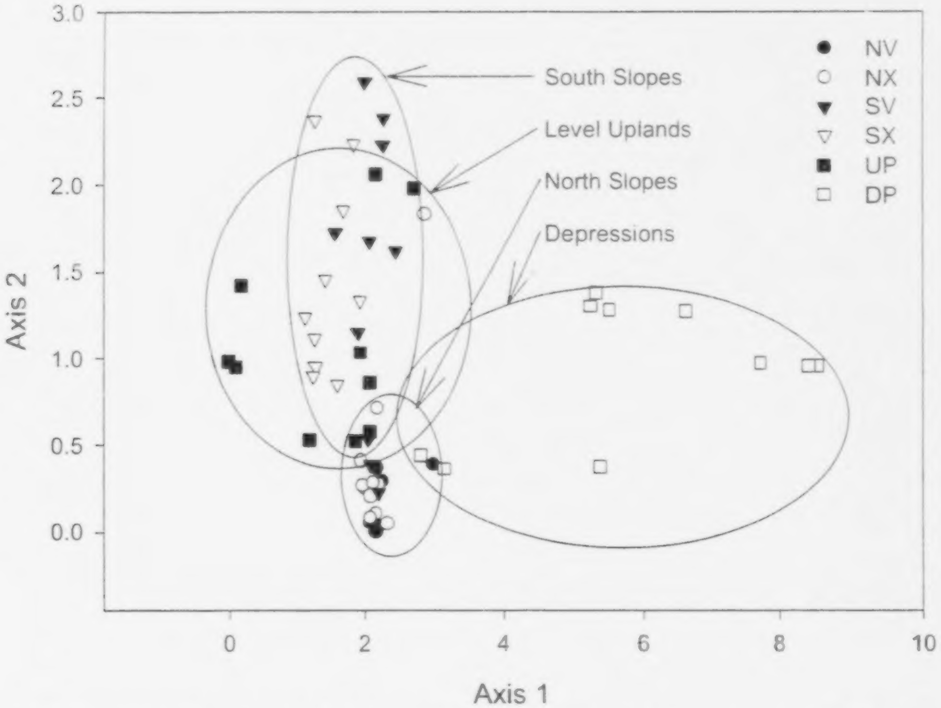

**Figure 1.6** Scatterplot based on Axis 1 and Axis 2 of Detrended Correspondence Analysis for 2003 species composition on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements at Macrorie, SK. Individual landscape elements are grouped visually as all south aspect sites (South Slopes), all level upland sites (Level Uplands), all north aspect sites (North Slopes) and all depression sites (Depressions).

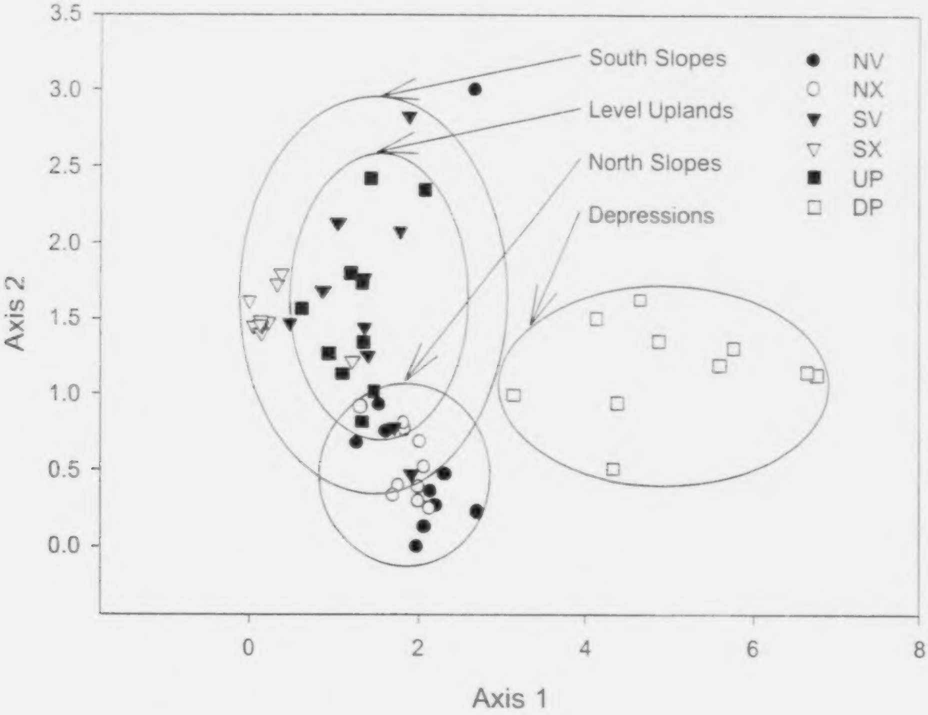

**Figure 1.7** Scatterplot based on Axis 1 and Axis 2 of Detrended Correspondence Analysis for 2004 species composition on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements at Macrorie, SK. Individual landscape elements are grouped visually as all south aspect sites-excluding one outlier (South Slopes), all level upland sites (Level Uplands), all north aspect sites (North Slopes) and all depression sites (Depressions).

Forbs and shrubs with the greatest canopy cover in both years were *Pulsatilla patens* (L.) P. Mill. (prairie crocus), *Rosa arkansana* Porter (prairie rose), *Artemisia frigida* Willd. (fringed sage), and *Anemone Canadensis* L. (Canada anemone) (Tables 4.7 and 4.8). Graminoids with the greatest canopy cover were plains rough fescue, western wheatgrass, needle-and-thread, western porcupine grass and *Carex pensylvanica* Lam. (sun loving sedge). Canopy cover of plains rough fescue was greatest on the north-facing and SV landscape elements in both years. Canopy cover of western wheatgrass was greatest on the SV and UP landscape elements in both years. Canopy cover of needle-and-thread and western porcupine grass was greatest on the SX landscape elements. Canopy cover of sun loving sedge was greatest on the SV landscape elements in both years.

Litter cover was greater on the UP, SV and DP landscape elements than all other landscape elements in 2003 (Tables 4.7 and 4.8). Litter cover was greater on the NV, SV, NX and UP landscape elements than all other landscape elements in 2004. Bare soil cover and clubmoss cover were greater on the SX landscape elements than all other landscape elements in 2003 and 2004.

**Table 1.7** Ground cover (%) and the cover of the five most common species on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements in 2003 at Macrorie, SK.

| Landscape | -- Ground Cover -- | | ------------ Forbs/Shrubs ------------ | | ------------ Graminoids ------------ | |
|---|---|---|---|---|---|---|
| Element | Type | Cover | Species | Cover | Species | Cover |
| NV | Litter | 24 c[1] | *Pulsatilla patens* | 4 | *Festuca hallii* | 56 |
| | Bare soil | < 1 b | *Artemisia frigida* | 2 | *Carex pensylvanica* | 1 |
| | *Selaginella densa* | 0 b | *Anemone canadensis* | 2 | *Hesperostipa curtiseta* | 1 |
| | | | *Astragalus flexuosus* | 1 | *Elymus trachycaulus* | 1 |
| | | | *Rosa arkansana* | 1 | *Pascopyrum smithii* | 1 |
| NX | Litter | 25 bc | *Pulsatilla patens* | 4 | *Festuca hallii* | 48 |
| | Bare soil | 1 b | *Artemisia frigida* | 3 | *Pascopyrum smithii* | 5 |
| | *Selaginella densa* | 1 b | *Rosa arkansana* | 2 | *Hesperostipa curtiseta* | 2 |
| | | | *Campanula rotudifolia* | 1 | *Carex pensylvanica* | 1 |
| | | | *Thermopsis rhombifolia* | 1 | *Hesperostipa comata* | 1 |
| SV | Litter | 32 ab | *Rosa arkansana* | 3 | *Festuca hallii* | 20 |
| | Bare soil | 1 b | *Artemisia frigida* | 2 | *Carex pensylvanica* | 9 |
| | *Selaginella densa* | 2 b | *Artemisia ludoviciana* | 2 | *Hesperostipa curtiseta* | 9 |
| | | | *Pulsatilla patens* | 2 | *Hesperostipa comata* | 7 |
| | | | *Anemone canadensis* | < 1 | *Pascopyrum smithii* | 6 |
| SX | Litter | 19 c | *Rosa arkansana* | 6 | *Hesperostipa comata* | 27 |
| | Bare soil | 7 a | *Artemisia frigida* | 3 | *Hesperostipa curtiseta* | 7 |
| | *Selaginella densa* | 8 a | *Pulsatilla patens* | 3 | *Carex filifolia* | 6 |
| | | | *Phlox hoodii* | 1 | *Carex pensylvanica* | 5 |
| | | | *Pediomelum esculentum* | 1 | *Festuca hallii* | 4 |
| UP | Litter | 34 a | *Astragalus flexuosus* | 3 | *Festuca hallii* | 16 |
| | Bare soil | < 1 b | *Pulsatilla patens* | 3 | *Elymus lanceolatus* | 12 |
| | *Selaginella densa* | 1 b | *Artemisia frigida* | 1 | *Pascopyrum smithii* | 10 |
| | | | *Phlox hoodii* | < 1 | *Hesperostipa comata* | 9 |
| | | | *Tragopogon dubius* | < 1 | *Hesperostipa curtiseta* | 4 |
| DP | Litter | 27 abc | *Polygonum amphibium* | 8 | *Poa pratensis* | 11 |
| | Bare soil | 0 b | *Anemone canadensis* | 6 | *Festuca hallii* | 9 |
| | *Selaginella densa* | < 1 b | *Artemisia ludoviciana* | 2 | *Carex rostrata* | 8 |
| | | | *Thalictrum venulosum* | 2 | *Poa compressa* | 4 |
| | | | *Galium boreale* | 1 | *Carex spp.* | 4 |

[1] Means with the same letters within a cover type are not significantly different among landscape elements ($P = 0.05$).

**Table 1.8** Ground cover (%) and the cover of the five most common species on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements in 2004 at Macrorie, SK.

| Landscape | -- Ground Cover -- | | ----------- Forbs/Shrubs ----------- | | ------------ Graminoids ------------ | |
|---|---|---|---|---|---|---|
| Element | Type | Cover | Species | Cover | Species | Cover |
| NV | Litter | 48 a | *Anemone canadensis* | 4 | *Festuca hallii* | 39 |
| | Bare soil | 0 b | *Pulsatilla patens* | 3 | *Pascopyrum smithii* | 6 |
| | *Selaginella densa* | < 1 b | *Artemisia frigida* | 3 | *Elymus lanceolatus* | 4 |
| | | | *Vicia americana* | 1 | *Carex pensylvanica* | 3 |
| | | | *Stellaria spp.* | 1 | *Elymus trachycaulus* | 2 |
| NX | Litter | 46 a | *Pulsatilla patens* | 5 | *Festuca hallii* | 38 |
| | Bare soil | 0 b | *Rosa arkansana* | 5 | *Elymus lanceolatus* | 4 |
| | *Selaginella densa* | 0 b | *Artemisia frigida* | 4 | *Carex pensylvanica* | 4 |
| | | | *Thermopsis rhombifolia* | 2 | *Elymus trachycaulus* | 2 |
| | | | *Campanula rotudifolia* | 2 | *Hesperostipa comata* | 2 |
| SV | Litter | 48 a | *Rosa arkansana* | 7 | *Festuca hallii* | 16 |
| | Bare soil | 1 b | *Pulsatilla patens* | 2 | *Carex pensylvanica* | 12 |
| | *Selaginella densa* | < 1 b | *Artemisia frigida* | 2 | *Hesperostipa comata* | 10 |
| | | | *Vicia americana* | 1 | *Hesperostipa curtiseta* | 9 |
| | | | *Artemisia ludoviciana* | 1 | *Pascopyrum smithii* | 8 |
| SX | Litter | 27 b | *Rosa arkansana* | 7 | *Hesperostipa comata* | 25 |
| | Bare soil | 6 a | *Pulsatilla patens* | 3 | *Carex filifolia* | 13 |
| | *Selaginella densa* | 9 a | *Artemisia frigida* | 3 | *Hesperostipa curtiseta* | 12 |
| | | | *Pediomelum esculentum* | 2 | *Carex pensylvanica* | 8 |
| | | | *Liatris punctata* | 1 | *Festuca hallii* | 2 |
| UP | Litter | 43 a | *Pulsatilla patens* | 6 | *Elymus lanceolatus* | 15 |
| | Bare soil | 1 b | *Artemisia frigida* | 2 | *Festuca hallii* | 15 |
| | *Selaginella densa* | < 1 b | *Astragalus flexuosus* | 1 | *Hesperostipa comata* | 13 |
| | | | *Vicia americana* | 1 | *Carex pensylvanica* | 9 |
| | | | *Erigeron caespitosus* | 1 | *Pascopyrum smithii* | 8 |
| DP | Litter | 33 b | *Anemone canadensis* | 13 | *Poa pratensis* | 17 |
| | Bare soil | 0 b | *Taraxacum officinale* | 7 | *Carex rostrata* | 10 |
| | *Selaginella densa* | 0 b | *Polygonum amphibium* | 7 | *Carex pensylvanica* | 5 |
| | | | Unknown1 | 3 | *Pascopyrum smithii* | 4 |
| | | | *Mentha arvensis* | 3 | *Hordeum jubatum* | 4 |

[1] Means with the same letters within a cover type are not significantly different among landscape elements (P = 0.05).

Forb biomass was greatest on the DP landscape element in both years, lowest on the UP landscape element in 2003 and the SV and UP landscape elements in 2004, and intermediate on other landscape elements ($P < 0.001$ in both years) (Table 1.9). Mowing reduced forb biomass by 41% in 2003 ($P = 0.016$), but the effect of mowing on forb biomass was not significant in 2004.

The effect of landscape element on standing-live biomass of graminoids was inconsistent between the two years (Table 1.9). The effects of landscape element and mowing interacted in 2003. Within the control treatment there was no difference among landscape elements ($P > 0.05$), but within the mowing treatment, standing-live biomass of graminoids was greatest on the

NV landscape element and least on the DP landscape element (P = 0.005). Mowing decreased standing-live biomass of graminoids in 2003 on the SV and DP landscape element by 19% and 68%, respectively (P = 0.036 and 0.008, respectively), but not on other landscape elements. The standing-live biomass of graminoids was greatest on the DP landscape element and least on the SX landscape element (P < 0.001). Mowing reduced standing-live biomass of graminoids on all landscape elements by 19% compared to control with a range from 5 to 32% depending on the landscape element (P < 0.001).

Mowing reduced standing-dead biomass of graminoids by 82 and 74% compared to the control for 2003 and 2004, respectively (P < 0.001 for both years, Table 1.9). The effect of landscape element on standing-dead biomass of graminoids was different in both years. The effects of landscape element and mowing interacted in 2003 and 2004 (P = 0.032 and 0.014, respectively). Standing-dead biomass of control plots was greatest on north-facing and UP landscape elements in 2003 and least on the south-facing and DP landscape elements. Of the mowed landscape elements, the standing-dead biomass of graminoids was greatest on the NX, UP, NV and SV landscape elements and least on the SX and DP landscape elements. In 2004, standing-dead biomass of graminoids among control landscape elements was greatest on the NV landscape element and least on the SX landscape element (P < 0.001). Within the mowed landscape elements, standing-dead biomass of graminoids was greatest on the UP landscape element and lower on all other landscape elements. Depending on the landscape element, the difference between control and mowing treatment was as great as 88% on the NV landscape element in 2003 and as little as 63% on the SX landscape element in 2004.

**Table 1.9** Above-ground biomass (mean ± SE, $g\ m^{-2}$) recorded in August of 2003 and 2004 on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements with control and April mowing at Macrorie, SK[1].

| Landscape Element | Forbs and Shrubs | | | Graminoids | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Standing-Live | | | Standing-Dead | | |
| | Control | Mowed | Mean | Control | Mowed | Mean | Control | Mowed | Mean |
| 2003 Growing Season | | | | | | | | | |
| NV | 16.7 ± 5.5 | 17.8 ± 4.4 | 17.2 b[3] | 119.3 ± 14.2 A a | 117.3 ± 16.8 A a | 118.3 | 494.3 ± 96.0 a | 58.1 ± 7.4 ab | 276.2 ± 85.7 |
| NX | 22.3 ± 14.3 | 19.0 ± 7.9 | 20.7 b | 110.0 ± 12.1 A a | 93.1 ± 5.4 A ab | 101.5 | 462.0 ± 100.4 a | 71.5 ± 11.5 a | 266.8 ± 80.7 |
| SV | 22.9 ± 6.2 | 13.0 ± 3.4 | 18.0 b | 96.8 ± 12.3 A a | 78.2 ± 8.6 B bc | 87.5 | 232.6 ± 17.1 b | 58.0 ± 9.6 ab | 145.3 ± 30.5 |
| SX | 20.0 ± 4.6 | 10.8 ± 2.4 | 15.4 b | 82.4 ± 10.2 A a | 75.7 ± 10.8 A bc | 79.1 | 172.5 ± 28.2 b | 41.8 ± 5.6 bc | 107.2 ± 25.7 |
| UP | 6.7 ± 3.9 | 6.8 ± 2.4 | 6.8 c | 149.4 ± 34.7 A a | 110.2 ± 14.1 A ab | 129.8 | 350.9 ± 85.9 ab | 65.5 ± 13.3 ab | 208.2 ± 62.8 |
| DP | 87.9 ± 42.0 | 36.0 ± 24.5 | 62.0 a | 140.7 ± 17.2 A a | 44.6 ± 15.3 B c | 92.6 | 167.8 ± 48.9 b | 26.6 ± 3.0 c | 97.2 ± 33.0 |
| Mean | 29.4 A[2] | 17.2 B | | 116.4 | 86.5 | | 313.4 ± 35.9 A | 53.6 ± 4.4 B | |
| 2004 Growing Season | | | | | | | | | |
| NV | 18.0 ± 4.6 | 37.0 ± 10.6 | 27.5 bc | 143.5 ± 17.6 | 100.8 ± 12.2 | 122.2 b | 275.0 ± 63.8 a | 41.9 ± 6.6 b | 158.5 ± 49.2 |
| NX | 36.6 ± 14.6 | 50.5 ± 6.6 | 43.6 b | 142.0 ± 25.1 | 96.7 ± 13.9 | 119.4 b | 219.9 ± 26.7 ab | 48.1 ± 5.1 b | 134.0 ± 31.4 |
| SV | 26.1 ± 4.2 | 17.2 ± 2.3 | 21.7 c | 108.7 ± 7.9 | 103.1 ± 8.7 | 105.9 bc | 197.1 ± 40.8 ab | 51.5 ± 4.1 b | 124.3 ± 31.0 |
| SX | 28.2 ± 3.7 | 30.4 ± 1.2 | 29.3 bc | 90.6 ± 10.8 | 81.0 ± 8.3 | 85.8 c | 75.4 ± 14.0 c | 27.3 ± 7.6 b | 53.7 ± 10.0 |
| UP | 18.0 ± 5.6 | 29.4 ± 12.3 | 23.7 c | 129.8 ± 9.6 | 95.8 ± 7.4 | 112.8 b | 244.6 ± 12.1 ab | 78.3 ± 14.1 a | 161.5 ± 29.1 |
| DP | 71.4 ± 16.6 | 78.7 ± 26.4 | 75.1 a | 165.2 ± 18.7 | 151.0 ± 34.7 | 158.1 a | 163.7 ± 39.9 bc | 53.4 ± 9.2 b | 108.5 ± 26.6 |
| Mean | 33.1 | 40.5 | | 130.0 A | 104.7 B | | 195.9 ± 18.3 A | 50.9 ± 4.0 B | |

[1] Some data were from A. Pantel, unpublished data.

[2] Means with the same lower case letters within a column and a year are not significantly different ($P = 0.05$).

[3] Means with the same upper case letters within a row and a plant group (i.e. Forb, Standing-Live, Standing-Dead) are not significantly different ($P = 0.05$).

Total above-ground biomass varied by landscape elements ($P = 0.010$) and mowing treatment ($P < 0.001$) in 2003 (Table 1.10). Total above-ground biomass was generally greatest on the NV and NX landscape elements, while total above-ground biomass was least on the SX landscape element. Mowing decreased total above-ground biomass by 67% compared to control. Landscape element and mowing interactively influenced total above-ground biomass in 2004 ($P = 0.013$). Within the control treatment, total above-ground biomass was greatest on the NV landscape element, intermediate on the DP, NX, UP and SV landscape elements and least on the SX landscape elements ($P < 0.001$). Within the mowing treatment, total above-ground biomass was greatest on the DP landscape element. Except on the SX and DP landscape elements, mowing reduced total above-ground biomass on all landscape elements.

**Table 1.10** Total above-ground biomass (mean ± SE, g $m^{-2}$) recorded in August on NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements with control and April mowing in 2003 and 2004 at Macrorie, SK.

| Landscape Element | 2003 | | | 2004 | | |
|---|---|---|---|---|---|---|
| | Control | Mowed | Mean | Control | Mowed | Mean |
| NV | 630.2 ± 92.2 | 193.2 ± 18.3 | 411.7 ± 85.3 a[1] | 436.4 ± 63.4 A a | 179.8 ± 10.3 B b | 308.1 ± 52.4 |
| NX | 594.3 ± 99.8 | 183.6 ± 13.6 | 389.0 ± 83.3 a | 398.5 ± 29.6 A ab | 195.3 ± 17.5 B b | 296.9 ± 37.5 |
| SV | 352.4 ± 23.8 | 149.1 ± 12.3 | 250.7 ± 36.2 bc | 331.9 ± 45.6 A b | 171.8 ± 9.0 B b | 251.9 ± 34.5 |
| SX | 275.0 ± 36.3 | 128.3 ± 15.1 | 201.7 ± 30.7 c | 194.2 ± 26.8 A c | 143.4 ± 11.2 A b | 168.8 ± 16.1 |
| UP | 507.0 ± 105.2 | 182.5 ± 12.6 | 344.8 ± 73.6 ab | 392.5 ± 19.7 A ab | 203.5 ± 9.3 B b | 298.0 ± 33.1 |
| DP | 396.4 ± 35.2 | 100.1 ± 38.0 | 248.2 ± 55.1 bc | 400.3 ± 27.2 A ab | 283.1 ± 48.7 A a | 341.7 ± 32.8 |
| Mean | 459.2 ± 36.3 A[2] | 156.1 ± 9.8 B | | 359.0 ± 20.6 | 196.1 ± 11.6 | |

[1] Means followed by the same lower case letters within a column are not significantly different ($P = 0.05$).

[2] Means followed by the same upper case letters within a row and a year are not significantly different ($P = 0.05$).

### 1.3.3 Variability in ghg flux rates as affected by landscape element and mowing

Carbon dioxide emissions from the soil surface were greater in 2004-2005 than in 2003-2004 (Figure 1.8). Carbon dioxide emissions were low before mid-May and after mid-September. Carbon dioxide flux rate peaked at 50 μg $CO_2$ $m^{-2}$ $s^{-1}$ in mid-May and was lowest in late October at 2 μg $CO_2$ $m^{-2}$ $s^{-1}$ in 2003-2004. In 2004-2005, $CO_2$ flux rates were highest in mid-July at 231 μg $CO_2$ $m^{-2}$ $s^{-1}$. The lowest $CO_2$ flux at 3 μg $CO_2$ $m^{-2}$ $s^{-1}$ was measured on 10 March 2005.

Carbon dioxide emissions were affected by the three-way interaction of landscape element, mowing and sample date in 2003-2004 ($P = 0.033$) and by the two-way interactions of landscape element and sample date, mowing and sample date, and landscape element and mowing in 2004-2005 ($P < 0.001$ for all three) (Figure 1.9). During spring and early summer of 2003, when the DP landscape element was flooded and therefore inaccessible, $CO_2$ flux rates were greatest from the SV, UP and NV landscape elements. Except on the final sampling day in 2003 when $CO_2$ flux rate was greatest on the SV landscape element, the $CO_2$ flux rate was always greatest on the DP landscape element after June. From September to October, the soils of the NV, NX and SX landscape element usually emitted less $CO_2$ than the soils of other landscape elements. In 2004-2005, the $CO_2$ flux rate was greatest from the DP landscape element on every sample date that landscape element was a significant factor in emissions rates. Carbon dioxide flux rates were greater in the mowing treatment than the control on most dates, ranging from 27 to 47% greater in 2003-2004 and 21 to 58% higher in 2004-2005.

Except on 7 April 2004 when $CH_4$ flue rates were positive, $CH_4$ flux rates from the soil were negative in both sampling seasons (Figure 1.10). In 2003-2004, mowing increased $CH_4$ uptake compared to control on 5 sample dates and 3 sample dates in 2004-2005. Differences in $CH_4$ consumption between mowing and control were as high as 58% on 29 July 2003 and 88% on 6 July 2004. Methane uptake was greater on control plots than on mowed plots only on 30 April 2003 ($P = 0.042$).

In 2003-2004, $CH_4$ flux was affected by the interaction between landscape element and sample date ($P < 0.001$) (Table 1.11). In the 2004-2005, landscape element and mowing ($P = 0.008$), landscape element and sample date ($P = 0.023$), and mowing and sample date ($P < 0.001$) interactively affected $CH_4$ flux rates. During the spring and early summer in 2003, the $CH_4$ consumption rate was greatest on the south-facing landscape elements and least on the NV and UP landscape elements. During summer, the $CH_4$ consumption rate was greatest on the DP landscape element, intermediate on the NX, SV and SX landscape elements and least on the UP and NV landscape elements.

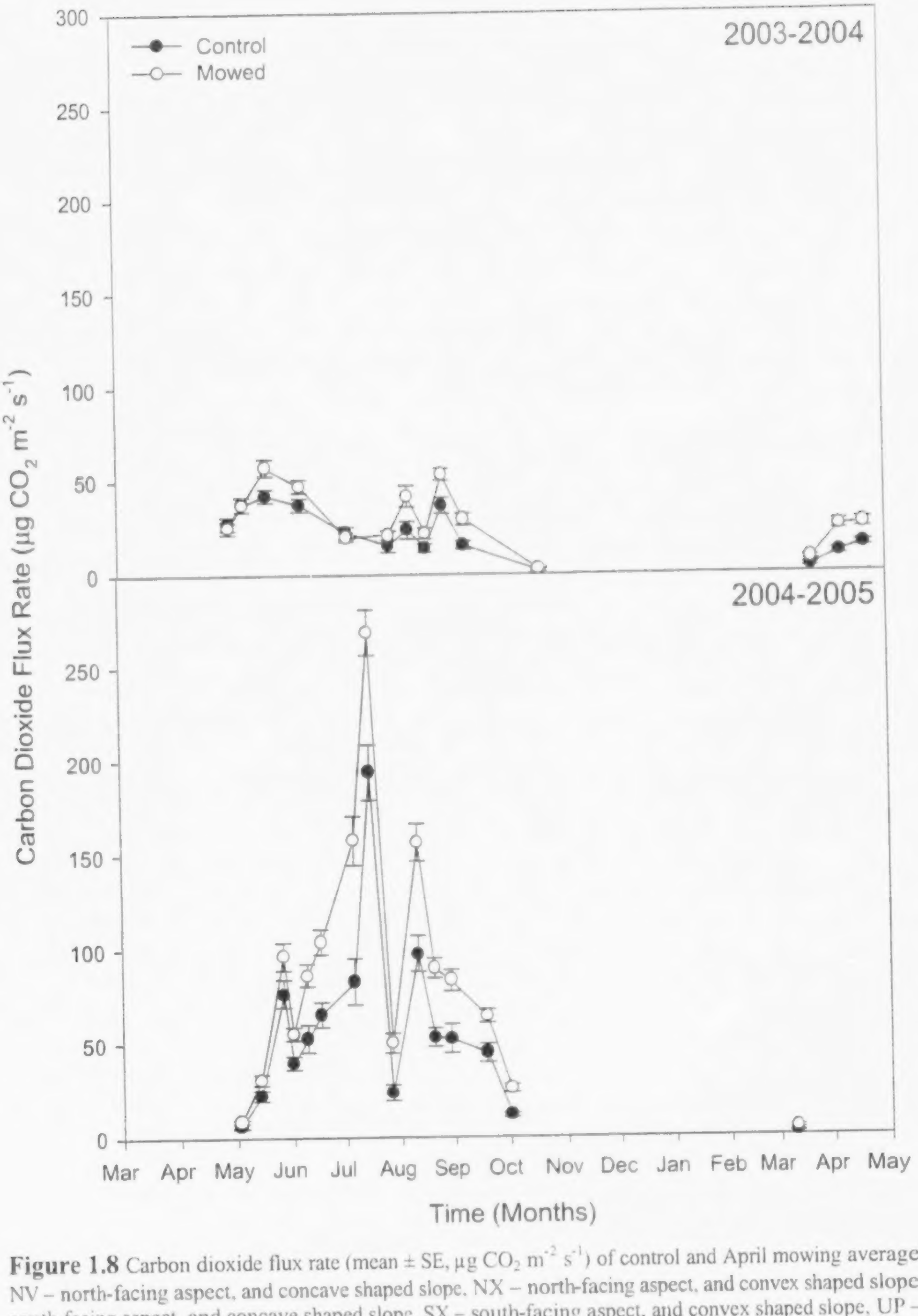

**Figure 1.8** Carbon dioxide flux rate (mean ± SE, µg $CO_2$ $m^{-2}$ $s^{-1}$) of control and April mowing averaged across NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements in 2003-2004 and 2004-2005 at Macrorie, SK.

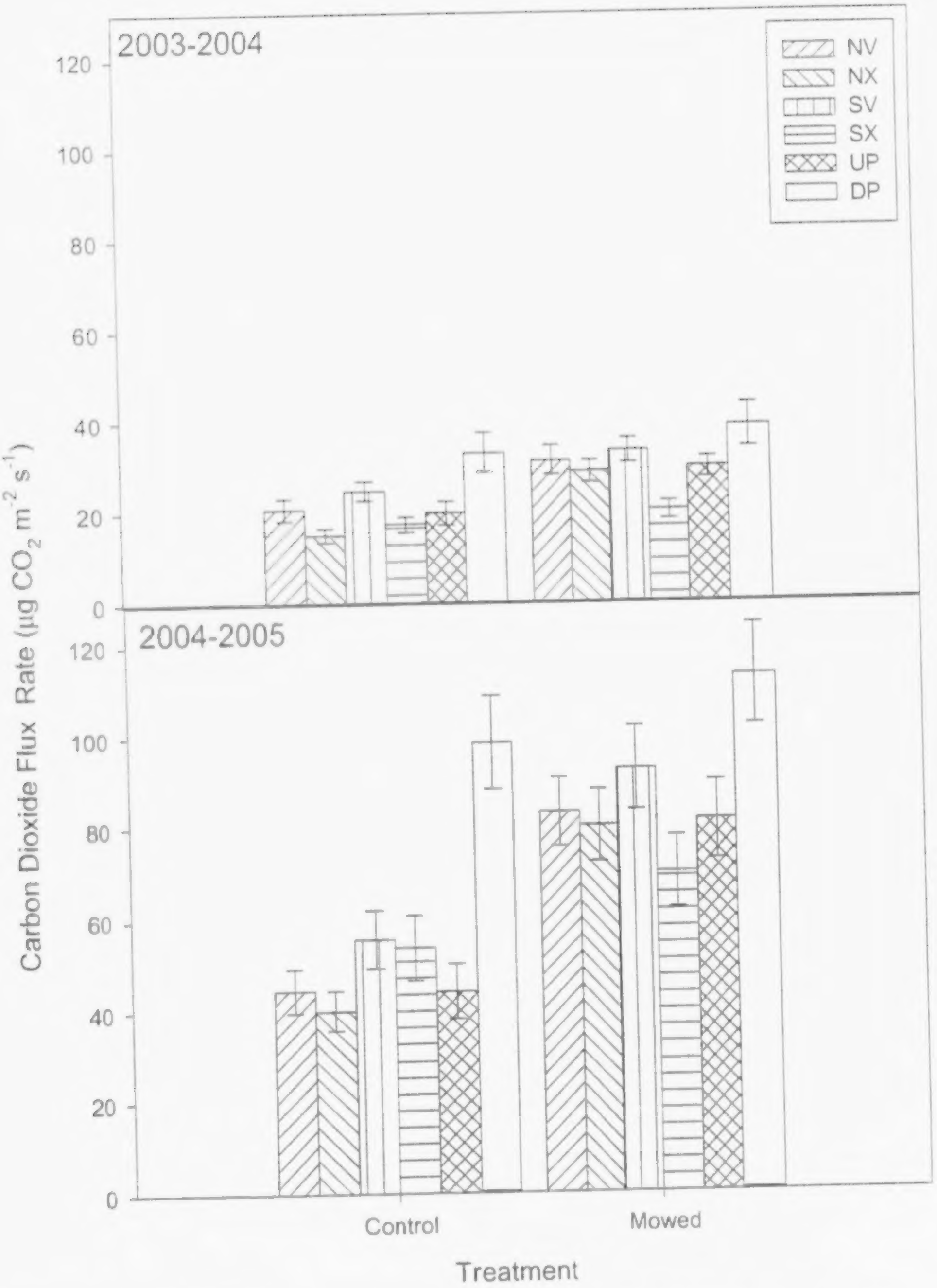

**Figure 1.9** Average carbon dioxide flux rate (mean ± SE, μg $CO_2$ $m^{-2}$ $s^{-1}$) of control and April mowing and NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements in 2003-2004 and 2004-2005 at Macrorie, SK.

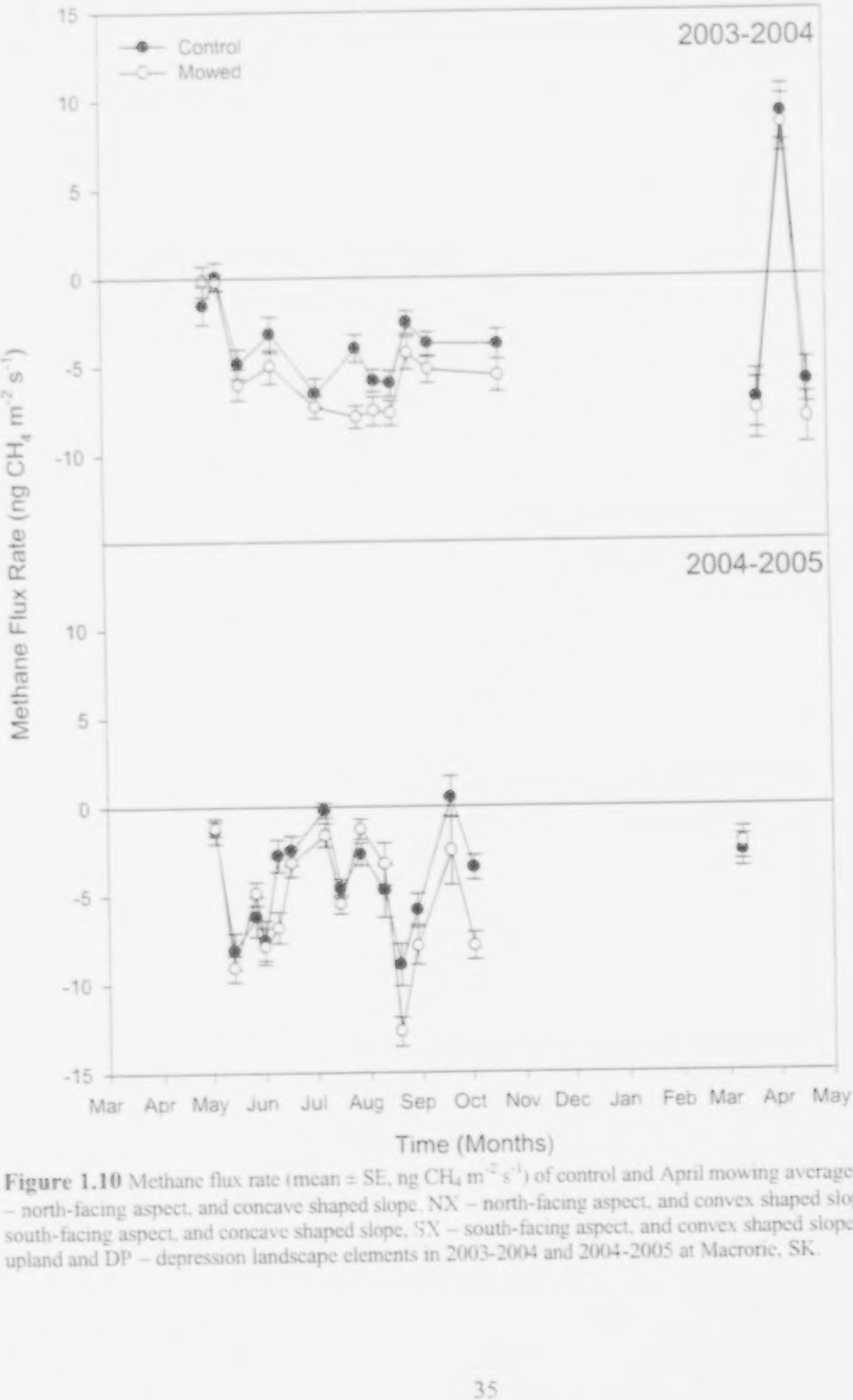

**Figure 1.10** Methane flux rate (mean ± SE, ng $CH_4$ $m^{-2}$ $s^{-1}$) of control and April mowing averaged across NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements in 2003-2004 and 2004-2005 at Macrorie, SK.

Within the control treatment, landscape element and sample date interactively influenced $CH_4$ flux rate in 2004-2005 ($P = 0.011$) (Table 1.11). Within the mowing treatment, the $CH_4$ consumption rate was greatest on the SX and NX landscape elements and least on the NV and UP landscape elements ($P = 0.001$). On sample dates when landscape element was a significant determinant of $CH_4$ flux, soils on the SX landscape element consumed the most, soils on the DP landscape elements consumed the least.

**Table 1.11** Average methane flux rate (mean ± SE, ng $CH_4$ $m^{-2}$ $s^{-1}$) for NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements with control and April mowing in 2003-2004 and 2004-2005

| Landscape | -------- 2003-2004 -------- | | | -------- 2004-2005 -------- | | |
|---|---|---|---|---|---|---|
| Element | Control | Mowed | Mean | Control | Mowed | Mean |
| NV | -1.55 ± 0.70 A[1] | -2.72 ± 0.70 B | -2.13 ± 0.50 | -2.58 ± 0.52 | -4.94 ± 0.54 b[2] | -3.76 ± 0.38 |
| NX | -2.88 ± 0.66 A | -4.57 ± 0.69 B | -3.73 ± 0.48 | -4.10 ± 0.67 | -6.26 ± 0.65 b | -5.18 ± 0.48 |
| SV | -3.61 ± 0.72 A | -4.43 ± 0.75 A | -4.02 ± 0.52 | -4.29 ± 0.62 | -5.58 ± 0.57 b | -4.93 ± 0.42 |
| SX | -4.86 ± 0.88 A | -5.12 ± 0.79 A | -4.99 ± 0.59 | -7.30 ± 0.91 | -6.39 ± 1.01 b | -6.85 ± 0.68 |
| UP | -1.86 ± 0.61[3] | -4.34 ± 0.83 | -3.10 ± 0.52 | -2.77 ± 0.60 | -3.22 ± 0.60 a | -3.00 ± 0.42 |
| DP | -2.08 ± 1.02 A | -3.46 ± 1.14 B | -2.77 ± 0.76 | -3.55 ± 0.57 | -5.09 ± 0.67 b | -4.32 ± 0.44 |
| Mean | -2.83 ± 0.32 | -4.13 ± 0.34 | | -4.11 ± 0.28 | -5.25 ± 0.29 | |

[1] Means followed by the same upper case letter within a row and a sampling season are not significantly different ($P = 0.05$).

[2] Means with the same lower case letter within a column and a sampling season are not significantly different ($P = 0.05$).

[3] Treatment means with no letter showed interaction between mowing and sample date.

During 2003-2004, landscape element and sample date interactively affected $N_2O$ flux rate ($P < 0.001$). Nitrous oxide flux rate was significantly greater than zero in 2003-2004 on only 8 sample dates (Figure 1.11). Nitrous oxide flux differed among landscape elements on 2 sample dates. On 22 March 2004, the DP landscape element had greater flux rates than all other landscape elements ($P < 0.001$). On 20 April 2004, $N_2O$ flux rate was greatest on the UP and SX landscape elements while $N_2O$ flux rate on north-facing landscape elements was the least ($P = 0.004$). Mowing affected $N_2O$ flux rates only on 29 August 2003 when mowing increased $N_2O$ emission rates compared to the control ($P = 0.022$).

During 2004-2005, sample date, landscape element and mowing all significantly influenced $N_2O$ flux rate. On 7 sample dates the average $N_2O$ flux rate was greater than zero (Figure 1.11). Nitrous oxide flux differed among landscape elements on 15 July 2004, 11 August 2004 and 30 August 2004. On 15 July 2004, the $N_2O$ flux rate from the SV, DP and UP landscape elements was greater and the $N_2O$ flux rate on all other landscape elements. On 11 August 2004, the $N_2O$ flux rate on the DP and SV landscape elements was greater than the $N_2O$ flux rate fromall other landscape elements. On 30 August 2004, the $N_2O$ flux rate from the DP landscape element was again the greatest while the $N_2O$ flux rates from all other landscape elements were similar to each other. Mowing increased $N_2O$ flux rates as a main effect ($P = 0.003$).

Weighted daily average $CO_2$-C emissions were influenced by the main effects of landscape element and mowing during 2003-2004 ($P = 0.006$ and $P = 0.022$ for landscape element and mowing, respectively) and 2004-2005 ($P < 0.001$ for both landscape element and mowing) (Table 1.12). Mowing increased weighted average daily $CO_2$-C flux by 18% in 2003-2004 and 36% in 2004-2005. In 2003-2004, the weighted average $CO_2$-C flux of control and mowing treatment ranged from 3.4 to 6.8 kg $CO_2$-C $ha^{-1}$ $d^{-1}$, depending on landscape element. Weighted daily average $CO_2$-C emissions were greatest on the DP landscape element and least on the NX and SX landscape elements. In 2004-2005, the range of weighted daily average $CO_2$-C emissions was 11.9 to 24.9 kg $CO_2$-C $ha^{-1}$ $d^{-1}$. Weighted daily average $CO_2$-C emissions were greatest on the DP landscape element.

Landscape element was a significant determinant of weighted daily average $CH_4$-C uptake in both sampling seasons ($P = 0.027$ in 2003-2004 and $P = 0.039$ in 2004-2005) (Table 1.12). In 2003-2004, weighted daily average $CH_4$-C uptake was greatest on the SX, SV and NX landscape elements, while weighted daily average $CH_4$-C uptake was least on the UP, DP and NV landscape elements. In 2004-2005, weighted daily average $CH_4$-C uptake was greatest on the SX and NX landscape elements and least on the NV and UP landscape elements. Mowing tended to increase weighted daily average $CH_4$-C uptake by 0.5 g $CH_4$-C $ha^{-1}$ $d^{-1}$ in 2003-2004 and 0.7 g $CH_4$-C $ha^{-1}$ $d^{-1}$ in 2004-2005.

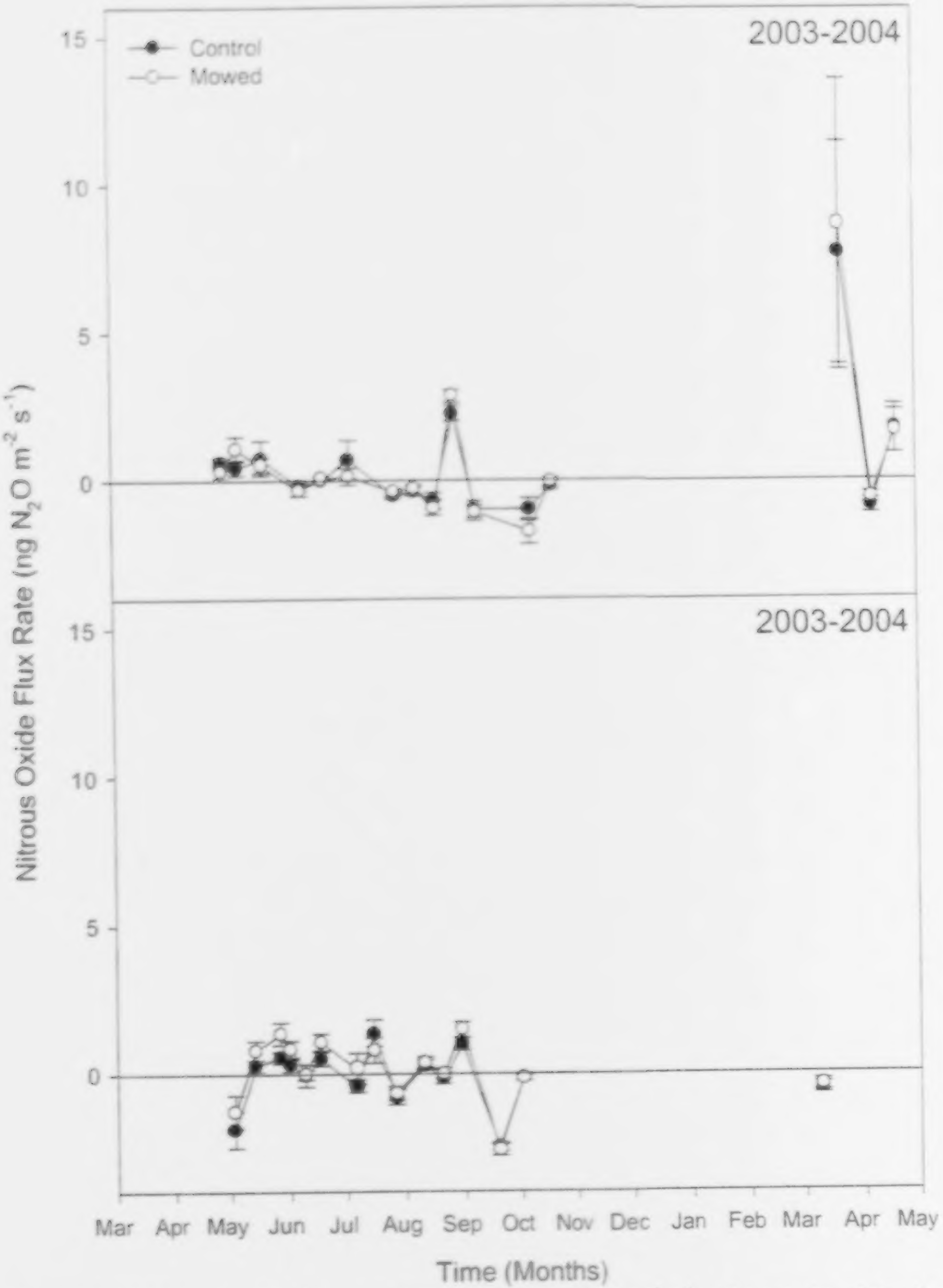

**Figure 1.11** Nitrous oxide flux rate (mean ± SE, ng $N_2O$ $m^{-2}$ $s^{-1}$) of control and April mowing averaged across NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements in 2003-2004 and 2004-2005 at Macrorie, SK.

Weighted daily average $N_2O$-N flux was influenced by landscape element in both sampling seasons ($P < 0.001$ and in 2003-2004 and $P = 0.028$ in 2004-2005) (Table 1.12). Weighted daily average $N_2O$-N flux was greatest on the DP landscape element in 2003-2004. The only positive daily average $N_2O$-N flux came from the DP and SV landscape elements while all other landscape elements had negative weighted daily average $N_2O$-N flux. Mowing tended to increase the weighted daily average $N_2O$-N flux compared to control.

Landscape element and mowing affect cumulative $CO_2$-C emissions in 2003-2004 ($P = 0.033$ and $P = 0.009$ for landscape element and mowing, respectively) and in 2004-2005 ($P < 0.001$ for landscape element and mowing) (Table 1.13). Cumulative $CO_2$-C emissions were greatest from the SV, UP, NV and DP landscape elements in 2003-2004. Cumulative $CO_2$-C emissions were greatest from the DP and SV landscape elements and cumulative $CO_2$-C emissions were least from the NX landscape element in 2004-2005. Mowing increased $CO_2$-C flux by 22 and 37% compared to the control in 2003-2004 and 2004-2005, respectively. Net $CO_2$-C emissions ranged from 1,533 kg $CO_2$-C $ha^{-1}$ on the UP landscape element with mowing treatment to 699 kg $CO_2$-C $ha^{-1}$ on the NX landscape element with control treatment in 2003-2004 and 4,336 kg $CO_2$-C $ha^{-1}$ from the DP landscape element with mowing treatment to 1,616 kg $CO_2$-C $ha^{-1}$ from the NX landscape element with control treatment in 2004-2005.

Landscape element had a significant impact on the net consumption of $CH_4$-C in both sampling seasons ($P = 0.013$ in 2003-2004 and $P = 0.023$ in 2004-2005) (Table 1.13). Net consumption of $CH_4$-C was greatest on south-facing landscape elements and least on the NV and DP landscape elements in 2003-2004. Net consumption of $CH_4$-C was greatest on the SX landscape element and was least on the UP landscape element in 2004-2005. Net consumption of $CH_4$-C on mowed landscape elements was 25 and 125 g $CH_4$-C $ha^{-1}$ more than net consumption of $CH_4$-C from landscape elements of the control treatment in 2003-2004 and 2004-2005, respectively. Net $CH_4$-C consumption ranged from 963 g $CH_4$-C $ha^{-1}$ on the SX landscape element to 435 g $CH_4$-C $ha^{-1}$ on the DP landscape element in 2003-2004 and from 761 g $CH_4$-C $ha^{-1}$ on the SX landscape element and 329 g $CH_4$-C $ha^{-1}$ on the UP landscape element in 2004-2005.

Landscape element influenced cumulative $N_2O$-N flux in 2003-2004 ($P < 0.001$) while landscape element and mowing influenced cumulative $N_2O$-N flux in 2004-2005 ($P = 0.17$ and $P = 0.48$, respectively) (Table 1.13). The largest cumulative $N_2O$-N emission was recorded on the DP landscape element in 2003-2004 while the largest cumulative $N_2O$-N emission was recorded on the DP and SV landscape elements in 2004-2005. Mowing decreased the $N_2O$-N flux by 26 g $N_2O$-N $ha^{-1}$ $season^{-1}$ in 2004-2005.

**Table 1.12** Weighted daily average carbon dioxide ($CO_2$) flux (mean ± SE, kg C $ha^{-1}$ ), methane ($CH_4$) flux (mean ± SE, g C $ha^{-1}$) and nitrous oxide ($N_2O$) flux (mean ± SE, g N $ha^{-1}$ ) from NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements with control and April mowing in 2003-2004 and 2004-2005 at Macrorie, SK.

| Landscape Element | $CO_2$ | | | $CH_4$ | | | $N_2O$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Control | Mowed | Mean | Control | Mowed | Mean | Control | Mowed | Mean |
| 2003-2004 | | | | | | | | | |
| NV | 4.7 ± 0.5 | 6.2 ± 0.5 | 5.4 ± 0.5 ab | -1.5 ± 0.4 | -2.5 ± 0.7 | -2.0 ± 0.4 a | 0.01 ± 0.16 | 0.09 ± 0.27 | 0.05 ± 0.14 b |
| NX | 3.1 ± 0.4 | 5.5 ± 1.3 | 4.3 ± 0.8 bc | -2.9 ± 0.4 | -3.1 ± 0.5 | -3.0 ± 0.3 abc | 0.20 ± 0.20 | -0.04 ± 0.06 | 0.08 ± 0.11 b |
| SV | 4.8 ± 0.2 | 6.5 ± 1.5 | 5.6 ± 0.8 ab | -3.1 ± 0.7 | -3.6 ± 0.3 | -3.3 ± 0.4 bc | 0.09 ± 0.04 | 0.03 ± 0.08 | 0.06 ± 0.04 b |
| SX | 3.3 ± 0.5 | 3.6 ± 0.0 | 3.4 ± 0.2 c | -4.4 ± 0.7 | -4.1 ± 0.9 | -4.2 ± 0.5 c | -0.06 ± 0.08 | -0.12 ± 0.09 | -0.09 ± 0.06 b |
| UP | 4.5 ± 0.6 | 6.7 ± 0.3 | 5.6 ± 0.6 ab | -1.9 ± 0.6 | -3.3 ± 0.8 | -2.6 ± 0.5 ab | > 0.01 ± 0.07 | 0.30 ± 0.19 | 0.15 ± 0.11 b |
| DP | 7.8 ± 0.5 | 5.8 ± 1.0 | 6.8 ± 0.7 a | -2.2 ± 0.3 | -2.5 ± 0.5 | -2.4 ± 0.3 a | 1.17 ± 1.09 | 1.51 ± 1.20 | 1.34 ± 0.73 a |
| Mean | 4.7 ± 0.4 B | 5.7 ± 0.4 A | | -2.7 ± 0.3 | -3.2 ± 0.3 | | 0.24 ± 0.19 | 0.29 ± 0.22 | |
| 2004-2005 | | | | | | | | | |
| NV | 8.6 ± 0.6 | 16.7 ± 0.8 | 12.7 ± 1.4 b | -1.8 ± 0.6 | -2.9 ± 0.5 | -2.3 ± 0.4 ab | -0.22 ± 0.08 | -0.14 ± 0.06 | -0.18 ± 0.05 b |
| NX | 7.8 ± 0.6 | 16.0 ± 1.9 | 11.9 ± 1.7 b | -2.2 ± 0.6 | -3.5 ± 0.6 | -2.9 ± 0.5 bc | -0.25 ± 0.05 | -0.14 ± 0.06 | -0.19 ± 0.04 b |
| SV | 11.1 ± 1.0 | 18.6 ± 1.8 | 14.9 ± 1.6 b | -2.4 ± 0.6 | -3.1 ± 0.3 | -2.8 ± 0.3 abc | -0.14 ± 0.15 | 0.30 ± 0.32 | 0.08 ± 0.18 a |
| SX | 10.3 ± 1.2 | 14.0 ± 0.7 | 12.2 ± 0.9 b | -3.9 ± 0.9 | -3.4 ± 0.9 | -3.7 ± 0.6 c | -0.20 ± 0.05 | -0.20 ± 0.07 | -0.20 ± 0.04 b |
| UP | 8.6 ± 0.6 | 16.1 ± 1.5 | 12.4 ± 1.5 b | -1.4 ± 0.3 | -1.8 ± 0.7 | -1.6 ± 0.4 a | -0.15 ± 0.11 | -0.01 ± 0.04 | -0.08 ± 0.06 ab |
| DP | 23.3 ± 4.2 | 26.4 ± 3.2 | 24.9 ± 2.5 a | -2.3 ± 0.6 | -3.1 ± 0.4 | -2.7 ± 0.4 abc | 0.15 ± 0.23 | 0.13 ± 0.15 | 0.14 ± 0.13 a |
| Mean | 11.6 ± 1.2 B | 18.0 ± 1.0 A | | -2.3 ± 0.3 | -3.0 ± 0.3 | | -0.13 ± 0.05 | -0.01 ± 0.07 | |

[1] Means followed by the same upper case letters within a row and a gas type (i.e. $CO_2$, $CH_4$ or $N_2O$) are not significantly different ($P = 0.05$).

[2] Means followed by the same lower case letters within a column and a gas type are not significantly different ($P = 0.05$)

**Table 1.13** Cumulative carbon dioxide (kg $CO_2$-C ha$^{-1}$ season $^{-1}$), methane (g $CH_4$-C ha$^{-1}$ season $^{-1}$) and nitrous oxide (g $N_2O$ -N ha$^{-1}$ season $^{-1}$) flux rates from NV – north-facing aspect, and concave shaped slope, NX – north-facing aspect, and convex shaped slope, SV – south-facing aspect, and concave shaped slope, SX – south-facing aspect, and convex shaped slope, UP – level upland and DP – depression landscape elements with control and April mowing in 2003-2004 and 2004-2005 at Macrorie, SK.

| Landscape Element | kg $CO_2$-C ha$^{-1}$ season$^{-1}$ | | | g $CH_4$-C ha$^{-1}$ season$^{-1}$ | | | g $N_2O$ -N ha$^{-1}$ season$^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Control | Mowed | Mean | Control | Mowed | Mean | Control | Mowed | Mean |
| | | | | | 2003-2004 | | | | |
| NV | 1068 ± 101 | 1404 ± 123 | 1236 ± 104 a | -351 ± 97 | -564 ± 157 | -458 ± 95 a | 3 ± 37 | 20 ± 61 | 11 ± 32 b |
| NX | 699 ± 91 | 1254 ± 302 | 976 ± 188 ab | -667 ± 81 | -713 ± 116 | -690 ± 64 ab | 46 ± 46 | -10 ± 13 | 18 ± 25 b |
| SV | 1095 ± 55 | 1471 ± 346 | 1283 ± 178 a | -696 ± 169 | -825 ± 68 | -761 ± 86 bc | 21 ± 9 | 6 ± 17 | 14 ± 9 b |
| SX | 754 ± 119 | 810 ± 6 | 782 ± 55 b | -997 ± 152 | -928 ± 201 | -963 ± 114 c | -13 ± 19 | -28 ± 20 | -21 ± 13 b |
| UP | 1016 ± 131 | 1533 ± 72 | 1275 ± 134 a | -443 ± 126 | -754 ± 178 | -598 ± 120 ab | >1 ± 16 | 67 ± 43 | 34 ± 26 b |
| DP[3] | 1322 ± 84 | 1147 ± 204 | 1234 ± 106 a | -376 ± 52 | -494 ± 92 | -435 ± 54 a | 198 ± 184 | 297 ± 236 | 248 ± 135 a |
| | 992 ± 62 B | 1270 ± 94 A | | -588 ± 69 | -713 ± 61 | | 42 ± 32 | 59 ± 44 | |
| | | | | | 2004-2005 | | | | |
| NV | 1794 ± 123 | 3463 ± 170 | 2628 ± 295 bc | -374 ± 128 | -594 ± 109 | -484 ± 87 ab | -45 ± 17 | -29 ± 12 | -37 ± 10 b |
| NX | 1616 ± 123 | 3313 ± 393 | 2465 ± 343 c | -459 ± 133 | -729 ± 114 | -594 ± 94 bc | -51 ± 11 | -29 ± 12 | -40 ± 9 b |
| SV | 2308 ± 215 | 3869 ± 373 | 3089 ± 330 b | -500 ± 127 | -646 ± 55 | -573 ± 70 bc | -28 ± 32 | 63 ± 67 | 17 ± 38 a |
| SX | 2138 ± 255 | 2910 ± 142 | 2524 ± 188 bc | -813 ± 191 | -709 ± 192 | -761 ± 129 c | -41 ± 10 | -41 ± 14 | -41 ± 8 b |
| UP | 1784 ± 130 | 3345 ± 317 | 2564 ± 306 bc | -287 ± 52 | -370 ± 148 | -329 ± 75 a | -31 ± 23 | -2 ± 9 | -17 ± 13 ab |
| DP | 3816 ± 683 | 4336 ± 517 | 4076 ± 413 a | -381 ± 95 | -514 ± 62 | -447 ± 58 ab | 24 ± 38 | 21 ± 25 | 22 ± 21 a |
| | 2243 ± 183 B | 3539 ± 153 A | | -469 ± 57 | -594 ± 51 | | -29 ± 10 B | -3 ± 13 A | |

[1] Means followed by the same upper case letters within a row and a gas type (i.e. $CO_2$, $CH_4$ or $N_2O$) are not significantly different (P = 0.05).
[2] Means followed by the same lower case letters within a column and a gas type are not significantly different (P = 0.05).
[3] Cumulative values for the DP landscape element were calculated from 122 days in 2003.

### 1.3.4 Relationships between environmental attributes, plant community characteristics and greenhouse gas flux

Significant environmental variables, as determined by the Monte Carlo permutation test, included in the CCA for 2003-2004 were mean gravimetric soil water, aspect, snow water equivalent, slope shape and cumulative $CO_2$ flux (Table 1.14). For the 2003-2004 sampling season, the first 4 axes of CCA explained a total of 28% of the variation in species composition (Table 1.15). Soil water and aspect were the two most important environmental factors controlling species composition. Soil water and snow water equivalent were strongly correlated with Axis 1 (correlation coefficient (r) = 0.904 and r = 0.742, respectively) (Table 1.16, Figure 1.12). Aspect and slope shape were both negatively correlated with Axis 2 (r = -0.842 and r = -0.359, respectively). Soil water was weakly correlated with aspect (r = -0.317) and positively correlated with slope shape (r = 0.237) (Table 1.17, Figure 1.12). Snow water equivalent and soil water were also correlated (r = 0.563).

**Table 1.14** Additional variance explained ($\lambda_A$), F Value and P Value of each environmental variable derived from manual forward selection using Monte Carlo permutation test with 9,999 unrestricted permutations in 2003-2004.

| Environmental Variable | $\lambda_A$ | F Value | P Value |
|---|---|---|---|
| Soil $H_2O$ | 0.71 | 8.33 | < 0.001 |
| Aspect | 0.35 | 4.38 | < 0.001 |
| Snow water equivalent | 0.30 | 3.95 | < 0.001 |
| Slope shape | 0.16 | 2.16 | 0.002 |
| Cumulative $CO_2$ flux | 0.17 | 2.30 | 0.001 |
| ---------------- $P > 0.01$ Cut off ---------------- | | | |
| Cumulative $N_2O$ flux | 0.13 | 1.87 | 0.075 |
| % Sand | 0.17 | 2.37 | 0.001 |
| % Litter | 0.11 | 1.73 | 0.026 |
| % Bare soil | 0.11 | 1.62 | 0.062 |
| Bulk density | 0.11 | 1.50 | 0.075 |
| % WFPS | 0.14 | 2.12 | 0.004 |
| Mowing treatment | 0.09 | 1.49 | 0.081 |
| $NH_4^+$ | 0.07 | 1.10 | 0.336 |
| % Clay | 0.06 | 0.82 | 0.683 |
| Total biomass | 0.04 | 0.70 | 0.799 |
| Cumulative $CH_4$ flux | 0.05 | 0.74 | 0.780 |
| PDIR | 0.05 | 0.70 | 0.786 |
| $NO_3^-$ | 0.03 | 0.51 | 0.961 |

**Table 1.15** Canonical Correspondence Analysis summary statistics from 2003-2004 species and environment data, including importance value of each axis (Eigenvalue: 0 = unimportant, 1 = very important), variance in species composition explained by each axis and cumulative variance explained.

| | Axis 1 | Axis 2 | Axis 3 | Axis 4 |
|---|---|---|---|---|
| Eigenvalue | 0.778 | 0.412 | 0.236 | 0.167 |
| Variance in species data: | | | | |
| % Explained | 13.9 | 7.3 | 4.2 | 3.0 |
| Cumulative % explained | 13.9 | 21.2 | 25.4 | 28.4 |

**Table 1.16** Correlation coefficients (r) from the Canonical Correspondence Analysis representing intra-set correlations between significant environmental variables and ordination axes in 2003-2004.

| Environmental Variable | Axis 1 | Axis 2 | Axis 3 | Axis 4 |
|---|---|---|---|---|
| Soil $H_2O$ | 0.904 | 0.393 | 0.160 | -0.055 |
| Aspect | -0.079 | -0.842 | 0.407 | -0.298 |
| Snow water equivalent | 0.742 | -0.043 | -0.638 | -0.195 |
| Slope shape | 0.447 | -0.359 | 0.040 | 0.326 |
| Cumulative $CO_2$ flux | 0.415 | -0.147 | 0.108 | 0.677 |

**Table 1.17** Correlations (r) from the Canonical Correspondence Analysis of significant environmental variables in 2003-2004.

| | Aspect | Slope shape | Snow water | Soil $H_2O$ | Cumulative $CO_2$ |
|---|---|---|---|---|---|
| Aspect | 1 | | | | |
| Slope shape | 0.057 | 1 | | | |
| Snow water | -0.215 | 0.217 | 1 | | |
| Soil $H_2O$ | -0.317 | 0.237 | 0.563 | 1 | |
| Cumulative $CO_2$ | 0.034 | 0.027 | 0.145 | 0.308 | 1 |

Species and environmental data from 2003 were spread widely along Axis 1 and much less along Axis 2 (Figure 1.12). The DP landscape element was at the extreme high end of the soil water, snow, cumulative $CO_2$ and slope shape gradients. Nitrous oxide flux and litter cover appear as short gradients, indicating a weak effect on species composition.

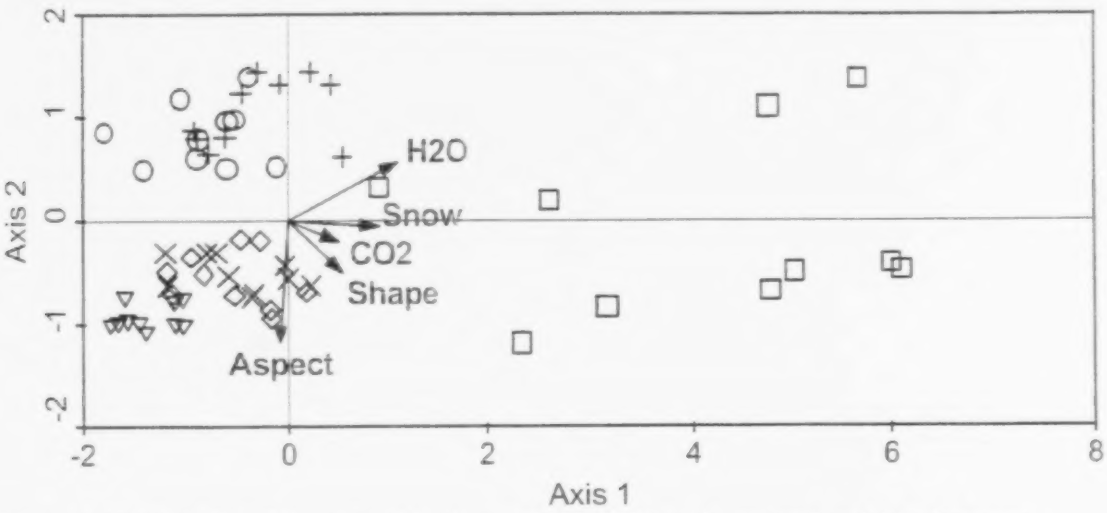

**Figure 1.12** Joint plot of linear combinations of 2003-2004 environmental variables (average gravimetric soil water content, snow water equivalent in the spring, cumulative $CO_2$ flux, slope shape and aspect) and species composition from control and April mowing and + NV – north aspect concave shape, ? NX – north aspect convex shape, ? SV – south aspect concave shape, ∇ SX – south aspect convex shape, × UP – level upland, ? DP – depression landscape elements at Macrorie, SK.

Significant environmental variables, as determined by the Monte Carlo permutation test, included in the CCA for 2004-2005 were mean gravimetric soil water, aspect, soil $NO_3^-$ content, % litter cover, cumulative $CO_2$ flux, % sand content, cumulative $CH_4$ flux and slope shape (Table 1.18). The first 4 axes explained 31% of the variance in species composition (Table 1.19). The strongest and most important variables for explaining species composition were soil water, aspect, % sand and litter cover. Soil water was positively correlated with Axis 1 ($r = 0.903$) and % sand was negatively correlated with Axis 1 ($r = -0.801$) (Table 1.20, Figure 1.13). Aspect was negatively correlated with Axis 2 ($r = -0.854$) and litter cover was positively correlated with Axis 2 ($r = 0.557$). Aspect was correlated with $H_2O$ ($r = -0.442$), % sand was correlated with slope shape ($r = -0.526$) and soil water ($r = -0.711$), and cumulative $CO_2$ flux was weakly correlated with % sand ($r = -0.377$) (Table 1.21, Figure 1.13).

**Table 1.18** Additional variance explained ($\lambda_A$), F Value and P Value of each environmental variable derived from manual forward selection using Monte Carlo permutation test with 9,999 unrestricted permutations in 2004-2005.

| Environmental Variable | $\lambda_A$ | F Value | P Value |
|---|---|---|---|
| % Soil $H_2O$ | 0.70 | 8.80 | < 0.001 |
| Aspect | 0.31 | 4.22 | < 0.001 |
| Soil $NO_3^-$ | 0.22 | 2.94 | < 0.001 |
| % Litter | 0.18 | 2.59 | < 0.001 |
| Cumulative $CO_2$ flux | 0.16 | 2.33 | 0.001 |
| % Sand | 0.15 | 2.26 | 0.002 |
| Cumulative $CH_4$ flux | 0.13 | 1.99 | 0.005 |
| Slope shape | 0.13 | 1.91 | 0.005 |
| ---------------- P = 0.01 Cut off ---------------- | | | |
| Mowing treatment | 0.09 | 1.52 | 0.052 |
| % Clay | 0.09 | 1.39 | 0.097 |
| Total biomass | 0.09 | 1.40 | 0.106 |
| Bulk density | 0.08 | 1.26 | 0.177 |
| % WFPS | 0.17 | 1.49 | 0.075 |
| % Bare soil | 0.07 | 1.08 | 0.357 |
| Soil $NH_4^+$ | 0.06 | 1.09 | 0.336 |
| PDIR | 0.07 | 1.16 | 0.257 |
| Cumulative $N_2O$ flux | 0.06 | 1.05 | 0.377 |

**Table 1.19** Canonical Correspondence Analysis summary statistics from 2004-2005 species and environment data, including importance value of each axis (Eigenvalue: 0 = unimportant, 1 = very important), variance in species composition explained by each axis and cumulative variance explained.

| | Axis 1 | Axis 2 | Axis 3 | Axis 4 |
|---|---|---|---|---|
| Eigenvalue | 0.777 | 0.370 | 0.282 | 0.199 |
| Variance in species data: | | | | |
| % Explained | 14.7 | 7.0 | 5.3 | 3.8 |
| Cumulative % explained | 14.7 | 21.7 | 27.0 | 30.8 |

**Table 1.20** Correlation coefficients (r) from the Canonical Correspondence Analysis representing intra-set correlations between significant environmental variables and ordination axes in 2004-2005.

| Environmental variable | Axis 1 | Axis 2 | Axis 3 | Axis 4 |
|---|---|---|---|---|
| % Soil $H_2O$ | 0.903 | 0.371 | 0.183 | -0.080 |
| Aspect | -0.145 | -0.854 | -0.160 | -0.115 |
| Soil $NO_3^-$ | 0.243 | 0.294 | -0.593 | -0.482 |
| % Litter | -0.296 | 0.557 | 0.024 | 0.223 |
| Cumulative $CO_2$ flux | 0.614 | -0.168 | -0.037 | 0.361 |
| % Sand | -0.801 | -0.114 | 0.279 | -0.170 |
| Cumulative $CH_4$ flux | 0.088 | 0.322 | -0.106 | 0.524 |
| Slope shape | 0.502 | -0.200 | -0.042 | 0.303 |

**Table 1.21** Correlations (r) from the Canonical Correspondence Analysis of significant environmental variables in 2004-2005.

| | Aspect | Slope shape | % Soil $H_2O$ | % Litter | Cumulative $CH_4$ flux | Cumulative $CO_2$ flux | % Sand | Soil $NO_3^-$ |
|---|---|---|---|---|---|---|---|---|
| Aspect | 1 | | | | | | | |
| Slope shape | -0.047 | 1 | | | | | | |
| % Soil $H_2O$ | -0.442 | 0.302 | 1 | | | | | |
| % Litter | -0.243 | -0.296 | -0.027 | 1 | | | | |
| Cumulative $CH_4$ flux | -0.187 | 0.187 | 0.121 | 0.033 | 1 | | | |
| Cumulative $CO_2$ flux | 0.050 | 0.212 | 0.481 | 0.083 | -0.110 | 1 | | |
| % Sand | 0.203 | -0.526 | -0.711 | 0.088 | -0.114 | -0.377 | 1 | |
| Soil $NO_3^-$ | -0.076 | 0.225 | 0.253 | 0.173 | -0.106 | -0.012 | -0.311 | 1 |

The CCA joint plot for 2004-2005 showed a similar spread of species composition along environmental gradients as observed in 2003-2004 (Figure 1.13). Extending cumulative $CH_4$ flux in the opposite direction, indicating $CH_4$ consumption, places south-facing landscape elements on the high end of the cumulative $CH_4$ consumption gradient. Soil $NO_3^-$ content was positively correlated with cumulative $CH_4$ flux while cumulative $CO_2$ flux was positively correlated with slope shape. Aspect appeared to be negatively correlated with cumulative $CH_4$ flux gradients and uncorrelated with cumulative $CO_2$ flux. The DP landscape element is at the high end of $CO_2$ flux.

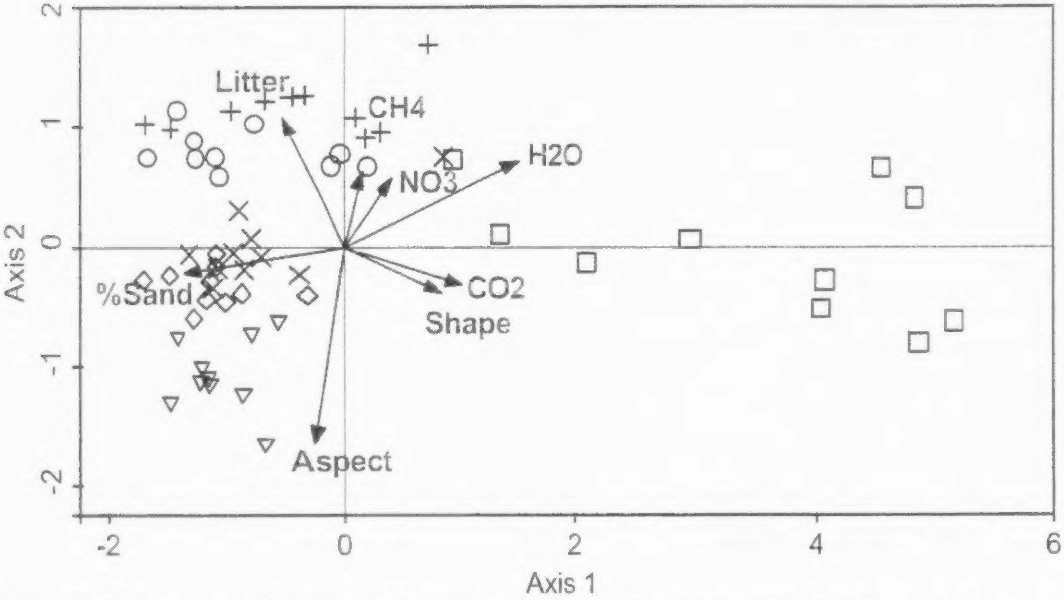

**Figure 1.13** Joint plot of linear combinations of 2004-2005 environmental variables (% litter cover, cumulative $CH_4$ flux, average soil $NO_3^-$, average gravimetric soil water content, cumulative $CO_2$ flux, slope shape, slope aspect and % sand content of soil) and species composition from control and April mowing and + NV – north aspect concave shape, ? NX – north aspect convex shape, ? SV – south aspect concave shape, ∇ SX – south aspect convex shape, × UP – level upland, ? DP – depression landscape elements at Macrorie, SK.

## 1.4. Discussion

Landscape element and mowing influenced plant community composition. Species richness varied with landscape element. There were fewer species on the UP landscape element than all other landscape elements in both years. Species richness decreases from upper to lower landscape positions in the Missouri Coteau (Tatina, 1994) and increases from south-facing slopes to north-facing slopes in the Mixedgrass Prairie of southern Alberta (Lieffers and Larkin-Lieffers, 1987). Increased habitat diversity is thought to increase species richness at the landscape level (Burnett et al., 1998). Soil microbe diversity is therefore expected to be lower on the UP landscape element because soil microbe diversity is positively correlated with plant species diversity (Metting, 1993).

Plant species evenness was influenced by landscape elements. Decreased species evenness on the north-facing landscape elements is likely due to the dominance of plains rough fescue in those areas. Plains rough fescue produces large quantities of biomass, out competing other species when temperature and soil water conditions are ideal (Looman, 1969). Species evenness was greatest on the north-facing slopes of coulees in the Mixedgrass Prairie possibly because other slopes had recently eroded (Lieffers and Larkin-Lieffers, 1987). In the current study, decreased species evenness on the north-facing landscape elements, was associated with lower soil temperatures and slightly higher WFPS (Chapter 4.1). Mowing increased species evenness in 2004, but not 2003. Mowing allows forbs to increase in canopy cover (Willms et al., 1986). Drought conditions of 2003 may have limited the effect of mowing.

Shannon-Wiener Diversity Index was greatest on the DP and SX landscape elements, likely due to growing conditions unique to those landscape elements. The DP landscape element tends to flood while the SX landscape element is often the driest part of the landscape. Dix and Smiens (1967) stated that species diversity is greatest on mesic sites, but least on very wet parts of the landscape. The DP landscape element can be flooded or remain dry, depending on the year, but increased soil water may support a more diverse plant community. Therefore, vegetation in the DP landscape element starts growing later than in other landscape elements and must survive dry conditions later in the summer. Barnes et al. (1983) states that species diversity and species richness is greatest on well-drained upper slopes with low $NO_3^-$ content. Soils on these landscape elements warm sooner, therefore allowing earlier growth than on other landscape elements in the spring (Cantlon, 1953), which may favour higher species diversity.

The pattern of plant species composition among landscape elements was similar in 2003 and 2004 as shown by the DCA. The DP landscape element can be separated from other landscape elements by Axis 1, which most likely reflects a soil water gradient. The north-facing and south-facing landscape elements were separated by Axis 2, which reflects aspect and/or temperature. Intuitively, the UP landscape elements are intermediate between north-facing and south-facing landscape elements along Axis 2. The DCA did not separate plots by mowing, indicating that treatment imposition did not cause immediate change in species composition. Grazing also did not change species composition of a grassland in Turkey (Amezaga et al., 2004).

Forb and shrub biomass was greater in 2004 than in 2003, possibly due to the higher precipitation in 2004 because precipitation is a major determinant of year-to-year changes in forb growth in the Mixedgrass Prairie (Gillen and Sims, 2004). Landscape element was an important factor in determining forb and shrub biomass in both years. Forb and shrub biomass was greatest in the DP landscape element in both years and least on the south-facing landscape elements. Forbs and shrubs made up a larger portion of the canopy cover in the DP landscape element than in other landscape elements (Chapter 5). Competition for N from grasses with extensive root systems on the south-facing landscape elements may have reduced forb and shrub growth (Raynaud and Leadley, 2004). On the other hand, water availability and water use may be more important for competition between forbs and grasses than N in semiarid areas (Booth et al., 2003). Mowing decreased forb and shrub biomass in 2003, when precipitation was below the long-term average, but not in 2004.

Standing-live biomass of graminoids was influenced by year-to-year variations in weather. Standing-live biomass of graminoids was greater in 2004 when precipitation increased compared to 2003. Standing-live biomass of graminoids is the first plant community characterisitc to recover after drought (Coupland, 1958). Landscape element also influenced standing-live biomass of graminoids. Sites that provide optimum growing conditions for plants have greater growth than areas that provide less than optimum growing conditions (Kormondy, 1996). The north-facing landscape elements receive less solar radiation, often have higher WFPS and greater soil N (Chapter 4.1) and generally had greater standing live biomass of graminoids. Soil C may be greater on these landscape elements because of the high plant production and C input to the soil.

April mowing decreased standing-live biomass of graminoids on the SV and DP landscape elements in 2003 and on most landscape elements in 2004. Mowing reduced standing-live biomass of graminoids even though most growth had not started. Among the months of mowing, early spring and late fall mowing were the least damaging to plants (A. Pantel, unpublished data). Mowing reduces the photosynthetic capacity of a plant, decreasing its C input to the soil via the roots (Biondini et al., 1998). On the other hand, reduced growth decreases plant competition for N, increasing soil N available for microbes (Corre et al., 1996). Mowing has similar influences on soil water; decreasing transpiration of the leaf canopy (Willms and Jefferson, 1993), but increasing evaporation of the soil (Willms, 1995).

Standing-dead biomass of graminoids was influenced by landscape element. Standing-dead biomass of graminoids and soil N were greater on north-facing landscape elements with control treatments imposed than on the south-facing with control treatments (Chapter 4.1). Mowing decreased standing-dead biomass of graminoids, therefore decreasing the contribution of plant matter to the soil. If repeated for many years, soil N may decrease (Biondini et al., 1998). Mowing removes plant matter, including soluble C, an important source of C for microbes that is easily leached from plant materials (Shelp et al., 2000).

Total above-ground biomass was influenced by landscape element and mowing in both years. Total above-ground biomass was similar to another study in the Mixedgrass Prairie (Ripley and Saugier, 1978), but nearly twice that reported from Mixedgrass Prairie in Alberta (Whysong and Bailey, 1975). High producing species such as plains rough fescue are present across the study area, but mesic areas appear ideal for this species and a large quantity of plant materials accumulated. Over time, accumulation of total above-ground biomass builds up soil N on the north-facing and DP landscape elements (Chapter 4.1). Above-ground biomass influences biotic processes by slowing root and soil microbe desiccation caused by the sun and the wind (Facelli and Pickett, 1991), making the soil environment more suitable for microbial activity. Total above-ground biomass retained on plots may have reduced the effects of landscape element and mowing on evaporation, allowing little variation of WFPS in space.

Mowing reduced total above-ground biomass and the relative reduction was most severe on the SX landscape element in both years, possibly due to slower plant regrowth compared to other landscape elements (A. Pantel, unpublished data). Reducing total above-ground biomass had no affect on soil temperature. Decreasing soil temperature can slow microbial activity during the spring and fall (Paul and Clark, 1996). Precipitation events = 5 mm constitute approximately 70% of the precipitation of the Mixedgrass Prairie of Saskatchewan (Coldberg and Romo, 2003) and can be entirely absorbed by a litter layer (Couturier and Ripley, 1973; Facelli and Pickett, 1991). Litter can capture up to 200% of its oven-dried weight in water during precipitation events (Naeth et al., 1991), which is then exposed to evaporation and not added to the soil (Weaver and Rowland, 1952). Above-ground plant matter increases the infiltration of precipitation (Larson and Whitman, 1942; Hopkins, 1954), decreases run off (Willms, 1995) and maintains soil water (Willms et al., 1986). Therefore, above-ground plant material can change water dynamics that influence biotic processes (Willms et al., 1993). When water is severely limiting, increasing litter does not increase plant growth (Willms and Jefferson, 1993). Variability in the reduction of total above-ground biomass by mowing may have contributed to the variability in WFPS in time and space.

Carbon dioxide flux rates in this study were positive, presumably because of the respiration from soil microbes, roots and above-ground plant parts. Carbon dioxide respiration of the soil may be responding to coarse scale increases in N deposition and atmospheric $CO_2$ concentrations (Köchy and Wilson, 2001; Flanagan et al., 2002). Over time, the release of $CO_2$ is expected to closely match the uptake of $CO_2$ across the Northern Great Plains (Frank and

Dugas, 2001). Reeder and Schuman (2002) suggested that the Mixedgrass Prairie resists changes in total C by redistributing C within the soil profile.

Carbon dioxide flux rates are important for the measurement of soil activity, including microbial and root respiration. Carbon dioxide flux rates from the Mixedgrass Prairie of Wyoming are within the range from the current project (Lecain et al., 2000). Carbon dioxide flux rates are much higher on the Mixedgrass Prairie of North Dakota completely denuded of vegetation, likely due to the extra exposure of the soil to solar radiation and death of plants (Frank et al., 2002). The daily average flux rate from the current study is lower than that for arable agriculture systems (Schmidt et al., 2001). Tillage increases decomposition by breaking apart aggregates protecting organic matter from decomposition. Carbon dioxide emissions from a Mixedgrass Prairie soil from Saskatchewan indicated much greater soil respiration than the current study (Redmann and Abouguendia, 1978) possibly due to soil disturbance during soil handling in the former.

Carbon dioxide flux rates were greater in 2004-2005 than in 2003-2004. Year-to-year variation in precipitation and temperature are common in the Mixedgrass Prairies and are important for biotic and abiotic processes of the grassland ecosystem (Coupland, 1958; Bootsma, 1994). Standing-live biomass of graminoids also increased in 2004 compared to 2003. Increased precipitation directly increases $CO_2$ emissions by improving the growing conditions for plant roots and soil microbes (McCulley et al., 2005). Carbon dioxide flux is also indirectly increased by greater precipitation because increased plant growth during a wet year transports more photosynthate to the roots, which eventually benefits soil microbes (McCulley et al., 2005).

Within year fluctuations of $CO_2$ emissions are caused by changes in C availability, soil water and soil temperature (Bremer et al., 1998; Epstein et al., 1998; Frank and Dugas, 2001). Low soil temperatures can limit $CO_2$ flux (Bremer et al., 1998; Frank et al., 2002), as in the current study during the spring and fall. The peak of daily $CO_2$ flux in 2004 was similar in time to the peak of the soil temperatures. Periods of low $CO_2$ flux were similar in time to cold periods in the spring and fall, and hot and very dry periods during the summer for both years. Landscape elements influence $CO_2$ emissions through soil water and soil temperature.

The influence of landscape element on $CO_2$ flux rates, weighted average daily $CO_2$-C and cumulative $CO_2$-C emissions were similar to the influence of landscape element on plant community characteristics (Chapter 4.2). Compared to other landscape elements, soil temperature and soil water in the DP landscape element did not limit plant growth and $CO_2$ emissions. On the other hand, though $CO_2$ emissions were least on the SX landscape element where soil temperature was adequate for plant growth, water usually limited plant growth and $CO_2$ emissions. Carbon dioxide emissions recorded from the SX landscape element were less than $CO_2$ emissions recorded from the NX landscape element. Carbon dioxide respiration appears more responsive to changes in soil water than to changes in soil temperature. Typical of northern wetlands, the bulk density and the ratio of standing-dead biomass of graminoids to standing-live biomass of graminoids were low on the DP landscape element (Kantrud et al., 1989). Past haying may also have contributed to low standing-dead biomass of graminoids to standing-live biomass of graminoids ratio. Moist conditions produce greater plant production but also increase decomposition (Kantrud et al., 1989).

Mowing increased $CO_2$ flux rates, weighted average daily $CO_2$-C and cumulative $CO_2$-C emissions in both years. Grazing can increased $CO_2$ emissions by increasing plant photosynthesis and C transported to the roots (Lecain et al., 2000). Grazing, trampling associated with grazing and mowing also increases $CO_2$ emissions by increasing soil temperature, damaging roots and adding plant matter to the soil (Redmann, 1978; Bremer et al., 1998). Mowing decreased standing-dead biomass of graminoids while increasing $CO_2$ flux in the current study. Mowing often increases the absorption of solar radiation by the soil surface and could increase soil temperature thereby increasing soil respiration. In the current study, mowing did not increase soil temperature. Except on the SX and DP landscape elements, differences in weighted daily average $CO_2$ flux between control and the mowing treatment were large in all landscape elements.

Soils consumed $CH_4$ throughout the year as recorded from other non-flooded soils (Topp and Pattey, 1997). The exception was 7 April 2004, when $CH_4$ production was likely favoured and emissions were above zero. The production of $CH_4$ is possible during the snowmelt in the Mixedgrass Prairie (Wang and Bettany, 1995) or after rain (Chan and Parkin, 2001). Methane is often simultaneously produced and consumed within the same soil column (Topp and Pattey, 1997). Methane production in soil that is not water saturated requires anaerobic conditions provided in some soil structures (Conrad, 1996). Clay was similar in all landscape elements of the current study. As soils are wetted, decreased $O_2$ diffusion into the soil increases $CH_4$ production over its consumption (Mosier et al., 1998b). As soils dry, diffusion of $O_2$ into the soil increases, anaerobic conditions decrease and consumption can be higher than production. Methane consumption in the current study is similar to that on the Shortgrass Prairie of Colorado (Mosier et al., 1991; Mosier et al., 1997) or pasturelands in Ontario (Dunfield et al., 1995).

Within year fluctuation of $CH_4$ consumption in the present study may have been caused by the variation of temperature and soil water. Cold temperatures are thought to decrease $CH_4$ oxidation (Potter et al., 1996), but consumption was least during summer when the soil temperature was greatest. Drying the soil reduces anaerobic microsites and methanotrophic activity, while wetting the soil has the opposite effect (Schnell and King, 1996). Except in the fall of 2003 when soil water was limited, $CH_4$ consumption of soil was greatest at the beginning and the end of the sample season when soil water was also greatest.

Landscape element influenced $CH_4$ flux rates, weighted daily average $CH_4$-C and cumulative $CH_4$ consumption (Mosier et al., 1996; Torn and Harte, 1996) but the influence of these two factors on $CH_4$ flux rates was inconsistent over time. Methane uptake on the DP landscape element in 2003-2004 was among the greatest but became the least the following year. The DP landscape element was flooded in the spring of 2003, and $CH_4$ was likely produced during this inaccessible period. Measurements of GHG flux from the DP landscape element only began in 2003 when the soil in the DP landscape element dried. Despite accumulated more snow than all other landscape elements, the DP landscape elements did not flood in spring of 2004 and therefore the unique series of conditions that may have influenced $CH_4$ flux in 2003 could not have occurred. The changing soil water conditions of this landscape element may have been responsible for the changing $CH_4$ flux rates during the two years. Methane consumption recorded on the SX landscape element remained greater than $CH_4$ consumption recorded on other landscape elements possibly due to the lack of soil N, which can inhibit $CH_4$ oxidation (Hütsch, 2001). Nitrous oxide production, a soil process that is N-limited, can be inversely related to $CH_4$ oxidation (Mosier et al., 1991). That inverse relationship did not appear to occur in the present study, though the CCA from 2004-2005 suggests that $CH_4$ consumption and $NO_3^-$ may be negatively correlated. Methane consumption recorded on the SX landscape element conditions may have been low because $CH_4$ production was rarely favoured by conditions on that landscape element. Wetting very dry soils can increase $CH_4$ consumption (Schnell and King, 1996), therefore, precipitation may have increased $CH_4$ consumption on the SX landscape element the most. Methane consumption rate was high on the SV landscape element probably because soil temperature requirements were not exceeded and soil water was greater than on the SX landscape element. Methane consumption rate was the least on the NV landscape element because conditions sometimes decreased the $CH_4$ consumption to production ratio.

Mowing tended to increase $CH_4$ consumption. In soils where water impeded $CH_4$ consumption, mowing induced increase in soil temperature and decreased soil water, which could also increase $CH_4$ consumption (Mosier et al., 1998b). Removal of above-ground biomass also increases $CH_4$ consumption in the Tallgrass Prairie because of changes in soil temperature and soil water (Tate and Striegl, 1993). The relationship between mowing and WFPS and mowing and $CH_4$ consumption, however, was not consistent in the present study. Mowing increased, decreased or did not change soil water and $CH_4$ depending on the time of year and the landscape element.

Nitrous oxide emissions were near zero on most sample dates in both sampling seasons. Soil N was low in the present study and the combination of competition for N and dry soils decreases $N_2O$ flux rates (Mummey et al., 1994). The rate of $N_2O$ production in the current study was similar to pasturelands in Saskatchewan (Corre et al., 1999) and less than arable lands from Saskatchewan and Alberta (Izaurralde et al., 2004). The mean soil $NO_3^-$ content of all landscape elements in the present study was below the 5 mg $NO_3^-$ kg dry soil$^{-1}$ threshold needed for denitrification to be the major source of $N_2O$ (Lemke et al., 1998). There is no relationship between WFPS and $N_2O$ production when denitrification occurs at low rates (Groffman and Tiedje, 1991). There is also no clear relationship between soil N and $N_2O$ when soil N was below the 5 mg threshold (Izaurralde et al., 2004). Water filled pore space was likely well below the threshold necessary for major $N_2O$ production in the current study. Therefore, even if WFPS or soil N increased to or above necessary thresholds for major $N_2O$ production, that process would still be limited by the other factor. Nitrous oxide production was similarly constrained by low soil N and low WFPS on all landscape elements in this study.

Negative $N_2O$ flux rates occured on several sample dates, but consumption of $N_2O$ was much less than recorded from Tallgrass Prairie in Kansas or forest in Belgium (Groffman and Turner, 1995; Goossens et al., 2001). Nitrous oxide consumption occurs only during the denitrification process and only when microbial activities responsible for $N_2O$ reductase are faster than that for NO (Beauchamp, 1997; Cavigelli and Robertson, 2001). Nitrous oxide uptake in a N-limited forest ecosystem was attributed to denitrifying bacteria consuming atmospheric $N_2O$ as a source of electron acceptors instead of $NO_3^-$ (Papen et al., 2001). Denitrification requires a WFPS of 60 to 90% (Bolan et al., 2004), a condition met only in frozen soils during the early spring of 2005 in the present study (Chapter 4.1). Nitrifier denitrification is a process that does not have the same WFPS requirement as denitrification and occurs in unsaturated soils of natural ecosystems (Wrage et al., 2004). Nitrifier denitrification utilises the denitrification process and may also consume $N_2O$.

Increased $N_2O$ flux rates from 2003-2004 to 2004-2005 can be explained by an increase in precipitation (Groffman and Turner, 1995; Groffman et al., 2000). Nitrous oxide production is greater following a dry year because $NO_3^-$ builds up in the soil during dry years (Mummey et al., 1994). Denitrification, the major process of $N_2O$ production, is most likely to occur in wet soil rather than drier soil (Müller et al., 2004).

Within year variation of $N_2O$ flux rates is due to fluctuations in weather, soil water, availability of $NO_3^-$ and rate of nitrification (Mummey et al., 1994; Bolan et al., 2004). The timing of the large positive flux that occurred 22 March 2004 is in keeping with the findings of other studies of large $N_2O$ emissions in spring (Lemke et al., 1999). Dead microbes and $NH_4^+$ fixed on soil particles add to available sources of $N_2O$ substrate during spring melt (Müller et al., 2002) because $N_2O$ producing microbes benefited from C and N leaked from microbes or roots damaged by the freeze thaw cycle (Wagner-Riddle and Thurtell, 1998; Bolan et al., 2004).

Landscape element and mowing induced differences in temperature and water, both contributing to differences in $N_2O$ flux (Corre et al., 1996; Izaurralde et al., 2004) in 2004. On 22 March 2004, the majority of $N_2O$ emissions were recorded on the DP and south-facing landscape elements. Plants cannot compete for soil N while dormant in early spring. Production of $N_2O$ by south-facing landscape elements in spring may be the result of decreased snow cover, earlier warming and earlier microbial activity on those landscape elements compared to north-facing landscape elements. Upper slope positions produce more $N_2O$ than lower slope positions in spring (Corre et al., 1996). For the rest of the sampling season, production of $N_2O$ from the DP landscape element constitutes most of the total $N_2O$ budget because of greater soil water and soil N than in other landscape elements. Nitrous oxide flux rates in spring of 2005 were low, probably because the soil was still too cold to support microbial activity. In soils with low denitrification rates where nitrification is the main source of $N_2O$, WFPS is not a good indicator of $N_2O$ (Groffman and Tiedje, 1991), but gravimetric soil water may be used to predict $N_2O$ emissions (Izaurralde et al., 2004). Nitrous oxide production has been positively correlated with biomass production (Groffman and Turner, 1995) but not in the current study (Chapter 4.2). Cooler, and usually wetter north-facing landscape elements were expected to have greater $N_2O$ flux, but competition for soil N between microbes and plants may have favoured plant growth given the large amount of plant biomass in this area. Pant growth and $N_2O$ production may have been soil N or soil water limited.

Mowing increased $N_2O$ production the most on the south-facing and UP landscape elements. Mowing decreased standing-live biomass of graminoids and may have therefore decreased the uptake of soil N, allowing more of it to be transformed into $N_2O$. Grazing increases $N_2O$ emissions but usually because of animal deposited N and trampling action (Ryden, 1985; De Klein et al., 2001). In fact, grazing increases denitrification more than mowing (Ryden 1986; Oenema et al., 1997).

The CCA joint plot for 2003-2004 shows that during a dry year the correlation between species composition and GHG flux rates was weak. Greenhouse gas flux from all landscape elements was low in 2003-2004, therefore the correlation between GHG flux and species composition was weak. Species composition, even though varying with landscape element, cannot be used to explain variations in GHG emissions in 2003-2004.

The 2004-2005 CCA joint plot shows the importance of the DP landscape element in determining landscape scale variation in GHG flux. The DP landscape element was at the high end of both $CO_2$ and $CH_4$ flux gradient arrows. The joint plot also showed that soil water content was correlated to GHG flux. Soil water content measured gravimetrically was as an important environmental variable, while WFPS, an indicator of anaerobic conditions, was not. Anaerobic conditions are important for high $N_2O$ emission rates but these conditions did not occur in the present study. Therefore, most GHG flux occurred in aerobic conditions and gravimetric soil water was probably more important than WFPS because gravimetric soil water controls general microbial activity and not just the activity of obligate anaerobic microbes. The chosen environmental variables only account for 28 to 31% of the variation in species composition. This suggests the variables measured may not have been the same ones that constrained species distribution.

# Part II: Changes in Soil Carbon and Biomass Production Along a Grassland-Shrub Gradient in the Mixed Prairie of Saskatchewan

## 2.1 Introduction

Shrub abundance has increased in arid and semiarid grasslands over the past 5 to 300 years and may continue to expand into grasslands in response to climate change (Archer 1989). These vegetation changes have been reported for grassland ecosystems worldwide (Brown and Archer 1999), including the Canadian prairies (Johnston and Smoliak 1968). This shift from grassland to shrubland is a significant issue because of its potential impact on ecosystem functions such as livestock production, wildlife habitats, and watershed protection (Biedenbender et al. 2004).

The invasion of shrubs into grassland also has the potential to alter the ecosystem carbon balance. Plant species composition, primary production, resource allocation, rooting depth, and soil faunal communities can be altered by shrub invasion and may subsequently modify the carbon balance (Jackson et al. 2002). Connin et al. (1997) concluded that the replacement of semiarid grassland by shrubs affects root biomass, litter production, soil organic carbon (SOC) cycling, nutrient availability and long-term soil carbon sequestration at the ecosystem scale. Soil organic carbon in the grassland ecosystem may also be affected by altered nutrient cycles (Trumbore 1997, Jackson et al. 2002) and by modified availability, quality, and/or quantity of carbon sources (Amundson 2001, Jackson et al. 2002). Other scientists concluded that shrub patches are islands of fertility in some landscapes because they trap wind-blown sediment, which leads to greater concentrations of materials and elements, such as carbon, in soil (Wezel et al. 2000).

These potential effects of shrub invasion in grassland are supported by Barth and Klemmedson (1978) whose study showed that SOC decreased as the distance from the center of velvet mesquite (*Prosopsis juliflora*) and palo verde (*Cercidium floridum*) increased in the Upper Sonoran Desert. Soil organic carbon in subtropical savanna of Texas also increased following woody plant encroachment (Hibbard et al. 2001). On the other hand, Hudak et al. (2003), who worked in South African savanna, concluded that SOC may initially increase with shrub encroachment but then decline if shrub densities become so great that understory graminoids are inhibited. Other factors, such precipitation, may also affect shrub invasion and SOC content.

A study conducted along a precipitation gradient in New Mexico, Colorado, and Texas revealed a negative relationship between precipitation and changes in SOC following invasion of by woody species such as mesquite (*Prosopsis* spp.), creosote (*Larrea* spp.), and juniper (*Juniperus* spp.) such that drier sites gained and wetter sites lost carbon (Jackson et al. 2002). In addition, losses of soil carbon at the wetter sites were substantial enough to offset greater above-ground plant biomass carbon in shrubs. Jackson et al (2002) therefore concluded that the estimates of carbon sequestration relying on greater aboveground carbon storage in woody species to compensate reduced storage in other fractions may be incorrect.

The objective of this study was to determine if invading snowberry (*Symphoricarpos occidentalis*) alters the soil carbon balance in the Prairie Ecozone of Saskatchewan. The null hypotheses that aboveground biomass, root biomass, and SOC are equal in snowberry shrub patches and adjacent grassland communities were tested. The hypothesis that response of SOC to shrub encroachment is similar in sandy and loamy soils was also tested.

## 2.2 Material and Methods

### 2.2.1 Site selection and description

Study sites are located in the Mixed Grassland and Moist Mixed Grassland ecoregions of the Prairie Ecozone in central and southern Saskatchewan (Table 2.1). Soil texture ranges from sandy to clayey and dominant plant species vary among the 9 study sites.

The nine study sites were chosen based on characteristics of shrub patches with less emphasis placed on management history. All shrub patches appeared to be well established and invading into native grassland as evidenced by an ecotone that spans more than 2 m between the shrub and grassland communities. Historical accounts were also provided by pasture managers to identify areas where they observed shrub cover increasing during their tenure at a particular pasture. Shrub patches dominated by snowberry with a diameter between 10 and 25 m were selected for this study. The composition of understory vegetation, which varies among study sites, was not used as a selection criteria.

Grazing intensity and history varied among the study sites (Table 2.1) but shrub patches where excessive grazing modified the structure and composition of the shrub community were omitted. In addition, none of the shrub patches were located in formerly cultivated grassland or where exotic species, such as smooth brome (*Bromus inermis*), were predominant. Grasslands that are located near facilities such as water, salt and mineral supplies were also avoided as were sites where hay and straw were fed to cattle during the winter. In addition, none of the study sites had signs of recent fires, such as the presence of charred shrub stems. The fire exclusion period for these study sites was estimated to be greater than 15 years.

### 2.2.2 Experimental design

The nine sites were used as replications for this study. A transect that originated near the centre of the shrub patch and extended into the grassland community was established at each site. Six, 2 x 2 m plots were positioned along each transect. The first plot was located in the shrub patch where snowberry was tallest and most dense. Two additional plots were positioned in the shrub patch interior while one was located near the midpoint of the shrub-grassland ecotone, and two were located in the grassland community. Distance between plots varied from about 3 to 5 m, depending on the size of the shrub patch.

**Table 2.1.** Descriptions of 9 sites in central and southern Saskatchewan selected for the shrub invasion study.

| Site | Soil texture, Landscape type, and Ecoregion | Dominant graminoids | Township | Grazing history |
|---|---|---|---|---|
| Abbott | Loamy,<br>Shallow lacustrine plain,<br>Moist Mixed Grassland | Plains rough fescue[1]<br>Kentucky bluegrass[2] | Tp39 R3 W3 | Protected from livestock for over 15 years |
| Kernen | Loamy,<br>Lacustrine plain,<br>Moist Mixed Grassland | Plains rough fescue<br>Porcupine grass[3] | Tp37 R4 W3 | Protected from livestock for over 15 years |
| Montrose North | Sandy,<br>Hummocky dunes,<br>Mixed grassland | Needle-and-thread[4]<br>Junegrass[5]<br>Blue grama[6]<br>Sedge[7] | Tp33 R7 W3 | Moderately to heavily grazed for over 15 years |
| Montrose South | Sandy,<br>Hummocky dunes,<br>Moist Mixed Grassland | Western wheatgrass[8]<br>Sedge | Tp33 R7 W3<br>(1 km south of Montrose North) | Moderately to heavily grazed for over 15 years |
| Biddulph | Sandy,<br>Hummocky dunes,<br>Moist Mixed Grassland | Needle-and thread<br>Junegrass | Tp 34 R5 W3 | Protected from livestock grazing for over 15 years |
| Rudy | Sandy,<br>Hummocky dunes,<br>Moist Mixed Grassland | Blue grama<br>Junegrass | Tp32 R5 W3 | Moderately to heavily grazed for over 15 years |
| Wilner | Loamy,<br>Kettled till plain,<br>Mixed grassland | Needle-and-thread<br>Sedge | Tp26 R2 W3 | Moderately to heavily grazed for over 15 years |
| Coop | Sandy,<br>Shallow lacustrine plain,<br>Mixed grassland | Needle-and-thread<br>Sedge | Tp21 R15 W3 | Moderately to heavily grazed for over 15 years |
| Matador | Loamy,<br>Lacustrine plain,<br>Mixed grassland | Northern wheatgrass<br>Junegrass | Tp20 R14 W3 | Protected from livestock grazing for over 15 years |

[1]*Festuca hallii* [2]*Poa pratensis* [3]*Stipa spartea* [4]*Hesperostipa comata* [5]*Koeleria macrantha* [6]*Bouteloua gracilis* [7]*Carex spp.* [8]*Pascopyrum smithii*

### 2.2.3 Data collection

Dependent variables measured or estimated included aboveground plant biomass, species composition (percent cover of vascular species), ground cover, soil organic carbon, bulk density, root biomass, and soil texture.

*2.2.3.1 Aboveground biomass, species composition, and ground cover*

Aboveground plant biomass (peak standing crop) was measured within each plot in August 2003 using a 1 x 1 m subplot. Litter on the soil surface was raked off first and all live and recently senesced plant materials were clipped at ground level. Litter and shrubs were stored separately while graminoids and forbs were pooled. All biomass samples were placed in paper bags, transported to the laboratory, and dried at 85° C in an oven to a constant mass. Biomass was measured within 2 m of the soil core collection points within each plot.

Species composition was determined by identifying and recording all species within eight, 0.5 x 0.5 m subplots per plot in July 2003. The eight subplots were positioned at the same location as standing crop was sampled and adjacent to the area where soil sample cores were extracted. Canopy cover was visually estimated to the nearest 5% for all species present in each subplot. Shrub canopy cover was estimated separately from the understory cover of forbs, graminoids and juvenile snowberry ramets. Species occupying less than 2.5% were scored at 1%. Mean percent cover per plot was based on the average of eight subplots.

Percent ground cover in each subplot was also estimated. Categories used for ground cover estimates included shrub leaf plus twig litter, graminoid and forb litter, bare ground, rock, and feces. Data were averaged over the eight subplots for each plot.

*2.2.3.2 Root biomass*

Soil samples for measuring root biomass were collected in July 2003 at each site. A hydraulic-powered punch with a 6.5 cm diameter core was used to collect 3 soil cores (subsamples) from 0 to 50 cm deep at each plot. Plant litter was removed from the soil surface prior to collecting the soil sample. Soil cores were divided into 0-3, 3-10, 10-20, 20-30, 30-40, and 40-50 cm depth increments and the three subsamples for each soil depth increment were pooled. Pooled samples for each depth were stored in paper bags, labeled, and transported to a storage facility at the University of Saskatchewan. All samples were stored at room temperature for more than 2 months before being processed.

Root biomass was determined by placing the soil sample on a 3 x 3 mm mesh screen was placed over a 20 L pail. A second screen with 1 x 1 mm mesh was draped inside the pail and underneath the 3 x 3 mm mesh so that it hung to the middle of the pail. Warm water was sprayed onto the soil and root samples with moderate force using a garden spray nozzle. After all soil was removed from the sample, roots remaining on the 3 x 3 mm screen were collected and sorted by diameter. All roots with a diameter greater than 3 mm were considered large. Medium roots were less than 3 mm in diameter and greater than 5 mm long. Fine roots were less than 1 mm in diameter and less than 5mm long. Materials in the medium sized category were identifiable as roots while the small plant fragments that comprise the fine samples were unidentifiable, consisted of small roots, fractions of roots, sloughed root epidermis, and fragmented and partly decomposed leaves and stems. The proportion of non-root plant material in the fine root category was indeterminate and appeared to be greatest for the 0-3 cm soil depth and diminishing with increasing soil depth.

Large and medium roots were collected from the 3 x 3 mm screen after all soil was washed off the sample. Roots remaining on top of the 3 x 3 mm screen were sorted into large and medium fractions. After all roots were collected from the 3 x 3 mm screen, the screen was removed from the pail and warm water was used to wash soil from the sample that remained on top of the 1 x 1 mm screen. After all soil was removed from the sample on the 1 x 1 mm screen, roots were collected and combined with the medium roots that were collected from the 3 x 3 mm screen as described above. After roots were collected from the 1 x 1 mm screen, they were removed from the pail. Plant materials floating in the water were collected with a hand-held sieve with mesh size less than 0.5 x 0.5 mm and treated as fine roots. All root biomass for each depth increment was stored in tin cans, oven dried at 85°C to a constant mass and subsequently weighed using a closed microbalance.

### *2.2.3.3 Soil bulk density*

Soil bulk density was determined using 100 $cm^{-3}$ bulk density tubes. Soil samples for bulk density were collected for the 0-3, 3-10, 10-20, 20-30, 30-40, and 40-50 cm depths. A hole was dug in each plot using a spade and the bulk density tubes were inserted at the midpoint of each depth increment. Soil tubes were pushed into the soil by hand at sandy sites and were hammered into the soil at all other sites. These tubes were hammered into the soil by placing a flat board on top and hammering them into the soil until the board was flush with the soil surface. Bulk density tubes were extracted from the profile by digging out a section of soil containing the tubes. Soil was removed from the exterior of the tubes and shaved off of the openings of the tubes using a knife. Soil samples from the cores at each depth increment for all plots were immediately placed in tin cans and transported to the laboratory. Soil samples were oven dried at 85° C to a constant mass and weighed.

### *2.2.3.4 Soil organic carbon*

Soil cores were collected in June 2003 using a hydraulic powered punch as described above for root biomass collection. Three soil cores (subsamples) were collected from each plot and within several cm of the locations of soil cores used for root biomass. Each soil core was divided into 0-3, 3-10, 10-20, 20-30, 30-40, and 40-50 cm depth increments. The three subsamples for each depth increment at each plot were pooled, placed in paper bags, labeled, transported to the University of Saskatchewan, and air dried at room temperature for more than 2 months before being processed.

Air dried soil samples were mechanically ground to increase accuracy and precision of SOC measurements. Recognizable plant materials were removed from soil samples before grinding by sieving or hand-picking with tweezers but some plant materials could not be removed from soil clods, particularly in loamy soils. Samples were coarsely ground using a soil grinder. A ball grinder was subsequently used to grind approximately 50 g of the coarsely ground soil. Soil was placed in the ball grinder for 2 to 3 minutes, or until the sample was a fine powdery texture (loamy soil) or until the sample was comprised exclusively of individual soil particles (sand). Soil samples were stored in plastic drum vials at room temperature after grinding.

A Leco CR-12 Carbon Analyzer was used to measure SOC (Wang and Anderson 1998). Approximately 0.15 g of the finely ground soil was placed into the carbon analyzer which was set at 840° C. Organic carbon in each sample was completely oxidized within two minutes. The carbon analyzer measured percent organic carbon in the soil sample and this percent was converted to mg of organic carbon $cm^{-3}$ after correcting for soil water content and bulk density of the soil sample.

### *2.2.3.5 Soil particle analysis*

The percent sand, silt, and clay in the A horizon of samples collected from each plot were determined using the hydrometer method similar to that described by Gee and Bauder (1979).

The method is based on the known relationship between density of soil solution and the proportion of particles in the suspension.

Samples from the 3 to 10 cm soil depth increment from each plot were oven-dried to a constant mass. Samples of 100 g (sandy soil) or 50 g (loamy soil) were then placed in a plastic bottle and combined with 100 mL of distilled water. The soil and water mixtures were shaken several times and 20 mL of sodium pyrophosphate ($Na_4P_2O_7$) were added to improve dispersion of soil particles in the solution. Additional distilled water was added to fill all plastic bottles to about two thirds of their capacity. Bottles were then stoppered and placed in an electric reciprocating machine to shake them until all particles were dispersed. Bottles with the samples were placed in the reciprocating shaker for 3 hours and subsequently allowed to stand for 24 hours followed by 3 additional hours of shaking.

After completion of shaking, individual samples were placed in a blender and the suspension was mixed for 30 seconds on low speed. Each sample was placed in a separate sedimentation cylinder after blending and distilled water was added to the solution until the total contents of the cylinder measured 1130 mL (50 g soil samples) or 1205 mL (100 g soil samples). A rubber stopper was secured inside the sedimentation cylinder after all of the soil and distilled water were added and the tube was shaken end-over-end for about 10 seconds to disperse the soil sample. Sedimentation cylinders were placed on a flat surface after shaking and the time was immediately recorded. The rubber stopper was then removed and a hydrometer was inserted into the solution. Hydrometer readings were taken at 40 seconds and 120 minutes after shaking. Percent sand (0.05 to 2.0 mm diameter), clay (less than 0.002 mm diameter), and silt (0.002 to 0.05 mm diameter) were calculated using equations 2.1 to 2.3.

$$\%\ \text{sand} = 100-(100*\text{hydrometer reading at 40 seconds/dry mass of soil sample}) \quad \text{(Eq. 2.1)}$$

$$\%\ \text{clay} = 100*\ (\text{hydrometer reading at 120 minutes/dry mass of soil sample}) \quad \text{(Eq. 2.2)}$$

$$\%\ \text{silt} = 100-(\%\ \text{sand} + \%\ \text{clay}) \quad \text{(Eq. 2.3)}$$

Data were used to determine the soil texture class for all six plots at each study site (Appendix 1). Soils comprised of greater than 50% sand were classified as sandy and those comprised of less than 50% sand were classified and loamy (Agriculture Canada Expert Committee on Soil Survey 1987).

### 2.2.4 Data analysis

Data from 3 plots in the shrub patch were averaged and compared to data from the single ecotone plot and to the average of the 2 plots located in the grassland. In addition, sites were classified as sandy or loamy for the analysis. Treatment effects were determined for plot location (shrub, ecotone, grassland), soil texture, and the interaction of plot location and soil texture.

The general linear model (GLM) analysis of variance (ANOVA) was used to analyze all data. Each depth of soil was analyzed separately (Zar 1999). A Tukey multiple comparison was conducted on all pairwise means when the treatment was significant (Zar 1999). All analyses were conducted using Minitab® Release 14.1 (Minitab Inc. 2003) and $P \leq 0.10$ was used as the significant level.

## 2.3 Results

### 2.3.1 Plant species composition along the gradient from grassland to shrub communities.

Shrub cover (snowberry) increased from grassland to the shrub community (Figure 2.1). Shrub cover in the shrub patch ranged from 82% at Wilner to 43% at Kernen and from 10 to 45% in the ecotone while shrubs were not present in grassland communities (Figure 2.1, Appendix 2.1). Graminoid cover varied widely among sites and communities within sites (Appendix 2.1). For example, sedges (*Carex* spp.) were found at all sites and ranged from 1 to 23% in shrub communities, 5 to 41% in ecotones, and 1 to 28% in grassland. Cover and composition of forbs and grasses was highly variable among sites (Appendix 2.1).

### 2.3.2 Soil organic carbon as affected by plant community gradient, soil texture and soil depth

Even though SOC varied widely among soil depths, it was not significantly different along the gradient from shrub to grassland at any depth increment or for the whole soil profile (0-50 cm) ($P > 0.1$) (Tables 2.2 and 2.3). Soil organic carbon generally decreased with increasing depth, so did the non-significant differences among the three community types. Non-significant differences of SOC content between shrub and ecotone communities increased in the 40-50 cm depth to the 0-3 cm depth (Table 2.2). Means for sandy sites across all soil depths ranged from 4.4 to 47.1 mg $cm^{-3}$ in the shrub community and from 4.7 to 31.9 mg $cm^{-3}$ in the ecotone (Table 2.3).

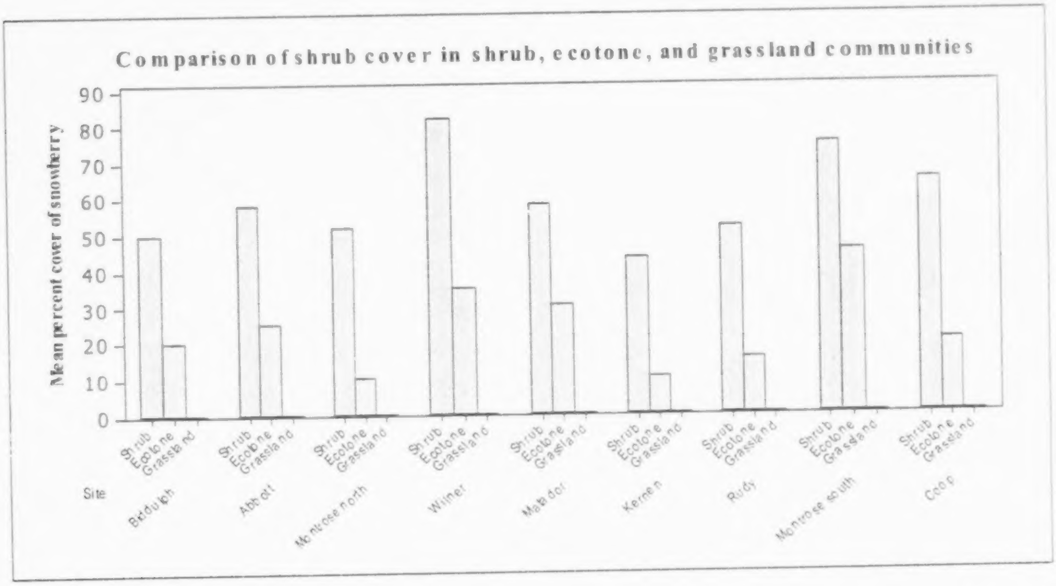

**Figure 2.1.** Mean percent snowberry cover in shrub, ecotone, and grassland communities at 9 study sites in the Prairie Ecozone of Saskatchewan. Values are means of 8 subplots per plot and 3, 1, and 2 plots in shrub, ecotone, and grassland, respectively.

The interactions between community type and soil texture were not significant for SOC at any soil depths. Soil texture had a significant effect on SOC at all depth increments ($P \leq 0.10$) (Table 2.2). with loamy sites having greater SOC at all depth increments than sandy sites (Table 2.3). Soil organic carbon was 15.9, 14.6, 9.5, 7.1, 8.1, and 3.2 mg $cm^{-3}$ more in loamy than sandy sites for the 0-3, 3-10, 10-20, 20-30, 30-40, and 40-50 cm depths, respectively (Table 2.2). Overall loamy sites also had 4.28 kg more SOC $m^{-2}$ than sandy sites over the soil profile. The difference between loamy and sandy sites was greatest in the 0-3 cm depth and decreased with increasing depth.

**Table 2.2.** Means comparisons for the effects of soil texture and plant community type along the gradient from grassland to shrub communities on soil organic carbon (SOC) in the Prairie Ecozone of Saskatchewan.

| Comparison | | | -------0-3 cm ------ | | | --------3-10 cm------- | | | -------10-20 cm----- | | | -----20-30 cm--- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ---------------------------------------------------(mg $cm^{-3}$)--------------------------------------------- | | | | | | | | | | | |
| Ec (Ecotone) | vs. | Sh (Shrub) | -3.11 | 11.43 | 0.96 | 1.37 | 6.56 | 0.98 | -0.03 | 4.49 | 1.00 | -1.67 | 2.94 | 0.84 |
| Gr (Grassland) | vs. | Sh | 4.18 | 11.43 | 0.93 | -0.52 | 6.56 | 1.00 | -0.17 | 4.49 | 1.00 | -1.98 | 2.94 | 0.78 |
| Gr | vs. | Ec | 7.29 | 11.43 | 0.80 | -1.89 | 6.56 | 0.96 | -0.13 | 4.49 | 1.00 | -0.31 | 2.94 | 0.99 |
| S (Sand) | vs. | L (Loam) | -15.93 | 8.72 | **0.08** | -14.61 | 4.41 | **0.00** | -9.45 | 3.08 | **0.01** | -7.08 | 1.93 | **0.00** |
| Sh x L | vs. | Sh x S | 2.70 | 15.80 | 0.95 | 13.19 | 8.31 | 0.62 | 13.11 | 5.73 | 0.24 | 10.79 | 3.41 | **0.05** |
| Ec x S | vs. | Sh x S | -15.20 | 14.90 | 0.99 | 0.42 | 7.84 | 1.00 | 2.96 | 5.40 | 0.99 | 1.54 | 3.21 | 1.00 |
| Gr x S | vs. | Sh x S | -1.40 | 14.90 | 0.83 | -1.48 | 7.84 | 1.00 | 1.72 | 5.40 | 1.00 | -0.24 | 3.21 | 1.00 |
| Ec x L | vs. | Sh x L | 12.00 | 16.60 | 0.98 | 2.55 | 8.76 | 1.00 | -3.78 | 6.04 | 0.99 | -5.68 | 3.59 | 0.62 |
| Gr x L | vs. | Sh x L | 11.20 | 16.60 | 0.98 | 0.68 | 8.76 | 1.00 | -2.53 | 6.04 | 1.00 | -4.15 | 3.59 | 0.85 |
| Ec x L | vs. | Ec x S | 29.90 | 15.80 | 0.43 | 15.32 | 8.31 | 0.46 | 6.37 | 5.73 | 0.87 | 3.57 | 3.41 | 0.90 |
| Gr x S | vs. | Ec x S | 13.80 | 14.90 | 0.93 | -1.90 | 7.84 | 1.00 | -1.24 | 5.40 | 1.00 | -1.78 | 3.21 | 0.99 |
| Gr x L | vs. | Ec x L | -0.80 | 16.60 | 1.00 | -1.87 | 8.76 | 1.00 | 1.25 | 6.04 | 1.00 | 1.53 | 3.59 | 1.00 |
| Gr x L | vs. | Gr x S | 15.30 | 15.80 | 0.92 | 15.34 | 8.31 | 0.46 | 8.86 | 5.73 | 0.64 | 6.88 | 3.41 | 0.37 |

[1] Difference in means between factors A and B.

**Table 2.2**. Continued

| Comparison | | | -------30-40 cm------- | | | -------40-50 cm------- | | | -------0-50 cm------ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ----------------------(mg $cm^{-3}$)------------------------- | | | | | | --------(kg $m^{-2}$)--------- | | |
| Ec Ecotone) | vs. | Sh (Shrub) | -0.96 | 2.50 | 0.92 | 0.01 | 2.01 | 1.00 | -0.22 | 1.63 | 0.99 |
| Gr (Grassland) | vs. | Sh | -1.21 | 2.50 | 0.88 | -0.81 | 2.01 | 0.91 | -0.32 | 1.63 | 0.98 |
| Gr | vs. | Ec | -0.26 | 2.50 | 0.99 | 3.00 | -0.82 | 0.91 | -0.10 | 1.63 | 1.00 |
| S (Sand) | vs. | L (Loam) | -8.08 | 1.22 | **0.00** | -3.22 | 1.49 | **0.04** | -4.28 | 0.99 | **0.00** |
| Sh x L | vs. | Sh x S | 9.48 | 2.21 | **0.00** | 4.22 | 2.78 | 0.66 | 4.75 | 1.87 | 0.16 |
| Ec x S | vs. | Sh x S | -0.50 | 2.08 | 1.00 | 0.30 | 2.62 | 1.00 | 0.04 | 1.76 | 1.00 |
| Gr x S | vs. | Sh x S | 0.20 | 2.08 | 1.00 | 0.24 | 2.62 | 1.00 | 0.04 | 1.76 | 1.00 |
| Ec x L | vs. | Sh x L | -1.53 | 2.33 | 0.99 | -0.35 | 2.93 | 1.00 | -0.55 | 1.97 | 1.00 |
| Gr x L | vs. | Sh x L | -2.98 | 2.33 | 0.79 | -2.13 | 2.93 | 0.98 | -0.78 | 1.97 | 1.00 |
| Ec x L | vs. | Ec x S | 8.46 | 2.21 | **0.01** | 3.57 | 2.78 | 0.79 | 4.16 | 1.87 | 0.27 |
| Gr x S | vs. | Ec x S | 0.70 | 2.08 | 1.00 | -0.06 | 2.62 | 1.00 | 0.00 | 1.76 | 1.00 |
| Gr x L | vs. | Ec x L | -1.45 | 2.33 | 0.99 | -1.78 | 2.93 | 0.99 | -0.23 | 1.97 | 1.00 |
| Gr x L | vs. | Gr x S | 6.31 | 2.21 | **0.09** | 1.86 | 2.78 | 0.98 | 3.94 | 1.87 | 0.32 |

**Table 2.3.** Soil organic carbon (SOC) along the gradient from grassland to shrub communities in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 3 shrub plots, 1 ecotone plot, and 2 grassland plots, respectively.

| | | | Soil depth (cm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Texture class | Site | Plot location | 0-50 | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | SOC (kg m$^{-2}$) | SOC (mg cm$^{-3}$) | | | | | |
| Sandy | Biddulph | Shrub | 4.5 | 17.6 | 13.7 | 10.8 | 8.3 | 5.9 | 5 |
| | | Ecotone | 5.9 | 21.3 | 9.7 | 20.2 | 11.8 | 6.2 | 7.2 |
| | | Grassland | 5.2 | 35.5 | 12.6 | 11.4 | 7.7 | 6.4 | 7.1 |
| | Rudy | Shrub | 5.2 | 32 | 19.2 | 12.6 | 7.6 | 5.3 | 3.3 |
| | | Ecotone | 8.4 | 38 | 42.7 | 23.4 | 13.4 | 3.2 | 2.2 |
| | | Grassland | 8.8 | 54.8 | 33.9 | 28.4 | 11.3 | 5 | 3.4 |
| | Montrose North | Shrub | 5.4 | 29.3 | 26.9 | 13.6 | 6.2 | 4.2 | 2.6 |
| | | Ecotone | 4.8 | 37.6 | 17.2 | 11.5 | 5.5 | 3 | 4.3 |
| | | Grassland | 5 | 31.7 | 14.1 | 9.4 | 8.4 | 8.1 | 4.9 |
| | Montrose South | Shrub | 5.3 | 56.1 | 13.6 | 10.6 | 7.8 | 4.9 | 3.4 |
| | | Ecotone | 4.1 | 24.3 | 16.9 | 7.7 | 6 | 4.1 | 4.3 |
| | | Grassland | 4.3 | 33.4 | 17.5 | 10.9 | 4.5 | 3.1 | 2.4 |
| | Coop | Shrub | 10.6 | 100.3 | 43.8 | 18 | 12.3 | 7.8 | 7.6 |
| | | Ecotone | 8 | 38.1 | 32.8 | 17.6 | 13.2 | 9.1 | 5.4 |
| | | Grassland | 7.9 | 72.8 | 31.7 | 14.1 | 9.1 | 6.5 | 5.3 |
| | **Means** | **Shrub** | **6.2** | **47.1** | **23.4** | **13.1** | **8.4** | **5.6** | **4.4** |
| | | **Ecotone** | **6.2** | **31.9** | **23.9** | **16.1** | **10.0** | **5.1** | **4.7** |
| | | **Grassland** | **6.2** | **45.6** | **22.0** | **14.8** | **8.2** | **5.8** | **4.6** |
| Loamy | Kernen | Shrub | 13.2 | 64 | 46.9 | 27.7 | 20.8 | 17 | 14.1 |
| | | Ecotone | 14.3 | 79.3 | 51.9 | 26.4 | 19.1 | 20.8 | 16.5 |
| | | Grassland | 14.7 | 60.3 | 46.5 | 41.5 | 28 | 16.8 | 10.4 |
| | Abott | Shrub | 11 | 47.1 | 47.8 | 28.2 | 20 | 14.4 | 0 |
| | | Ecotone | 10.3 | 35.8 | 36.7 | 34.8 | 15.6 | 15.8 | 0 |
| | | Grassland | 8.8 | 51.7 | 39.4 | 22 | 11.1 | 11.5 | 0 |
| | Wilner | Shrub | 13.2 | 61.6 | 31.1 | 36.2 | 25.8 | 18.5 | 11.7 |
| | | Ecotone | 11.7 | 100 | 48.5 | 19.2 | 12.9 | 10.8 | 10 |
| | | Grassland | 10.4 | 91.7 | 40.2 | 17.3 | 11.8 | 11.4 | 7.4 |
| | Matador | Shrub | 6.4 | 26.2 | 20.7 | 12.8 | 10.3 | 10.5 | 8.6 |
| | | Ecotone | 5.3 | 31.8 | 19.6 | 9.4 | 6.6 | 6.9 | 6.5 |
| | | Grassland | 6.8 | 39.9 | 23.1 | 14 | 9.4 | 8.8 | 8.1 |
| | **Means** | **Shrub** | **11.0** | **49.7** | **36.6** | **26.2** | **19.2** | **15.1** | **8.6** |
| | | **Ecotone** | **10.4** | **61.7** | **39.2** | **22.5** | **13.6** | **13.6** | **8.3** |
| | | **Grassland** | **10.2** | **60.9** | **37.3** | **23.7** | **15.1** | **12.1** | **6.5** |

### 2.3.3 Soil bulk density as affected by plant community gradient, soil texture and soil depth

Bulk density was significantly greater in shrub than grassland communities but differences between ecotone and shrub, and between grassland and ecotone were not significant (Tables 2.4, 2.5). Bulk density in the 0-3 cm increment was lower than all depth increments and bulk density in the 3-10 cm increment was lower than the 20-50 cm increments. Soil texture also had a significant effect on bulk density such that of sandy soils was 0.2 g $cm^{-3}$ greater than loamy soils.

**Table 2.4.** Means comparisons for bulk density along the gradient from grassland to shrub, in sandy and loamy soil, and throughout the soil profile for 9 sites located in the Prairie Ecozone of Saskatchewan.

| | Comparison | | Difference | | |
|---|---|---|---|---|---|
| Parameter | Factor A | Factor B | A-B (g $cm^{-3}$) | SE | P |
| Plant community | Ecotone | Shrub | 0.07 | 0.04 | 0.22 |
| | Grassland | Shrub | 0.09 | 0.04 | **0.09** |
| | Grassland | Ecotone | 0.02 | 0.04 | 0.88 |
| Soil texture | Loamy | Sandy | -0.20 | 0.04 | **0.00** |
| Soil depth (cm) | 3-10 | 0-3 | 0.28 | 0.06 | **0.00** |
| | 10-20 | 0-3 | 0.40 | 0.06 | **0.00** |
| | 20-30 | 0-3 | 0.47 | 0.06 | **0.00** |
| | 30-40 | 0-3 | 0.48 | 0.06 | **0.00** |
| | 40-50 | 0-3 | 0.50 | 0.06 | **0.00** |
| | 10-20 | 3-10 | 0.11 | 0.06 | 0.33 |
| | 20-30 | 3-10 | 0.18 | 0.06 | **0.02** |
| | 30-40 | 3-10 | 0.20 | 0.06 | **0.01** |
| | 40-50 | 3-10 | 0.22 | 0.06 | **0.00** |
| | 20-30 | 10-20 | 0.07 | 0.06 | 0.82 |
| | 30-40 | 10-20 | 0.08 | 0.06 | 0.71 |
| | 40-50 | 10-20 | 0.10 | 0.06 | 0.50 |
| | 30-40 | 20-30 | 0.01 | 0.06 | 1.00 |
| | 40-50 | 20-30 | 0.03 | 0.06 | 0.99 |
| | 40-50 | 30-40 | 0.02 | 0.06 | 1.00 |

**Table 2.5.** Soil bulk density along the gradient from grassland to shrub communities in the Prairie Ecozone of Saskatchewan.

| | | | Soil depth (cm) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Texture class | Site name | Plot l | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | Bulk density (g cm$^{-3}$) | | | | | |
| Sandy | Biddulph | shrub | 0.96 | 1.29 | 1.39 | 1.50 | 1.43 | 1.38 |
| | | ecotone | 1.00 | 1.36 | 1.39 | 1.61 | 1.53 | 1.56 |
| | | grassland | 0.95 | 1.03 | 1.36 | 1.40 | 1.45 | 1.52 |
| | Rudy | shrub | 0.82 | 1.16 | 1.34 | 1.48 | 1.36 | 1.40 |
| | | ecotone | 0.81 | 1.31 | 1.35 | 1.44 | 1.42 | 1.51 |
| | | grassland | 0.87 | 1.22 | 1.43 | 1.41 | 1.40 | 1.26 |
| | Mont N | shrub | 0.87 | 1.34 | 1.03 | 1.42 | 1.52 | 1.58 |
| | | ecotone | 1.16 | 1.46 | 1.40 | 1.55 | 1.47 | 1.48 |
| | | grassland | 1.13 | 1.38 | 1.42 | 1.46 | 1.46 | 1.45 |
| | Mont S | shrub | 0.95 | 1.18 | 1.35 | 1.35 | 1.35 | 1.28 |
| | | ecotone | 0.73 | 1.24 | 1.31 | 1.43 | 1.35 | 1.45 |
| | | grassland | 1.19 | 1.27 | 1.47 | 1.32 | 1.44 | 1.45 |
| | Coop | shrub | 1.06 | 1.40 | 1.47 | 1.52 | 1.52 | 1.68 |
| | | ecotone | 1.20 | 1.45 | 1.41 | 1.46 | 1.59 | 1.53 |
| | | grassland | 1.24 | 1.51 | 1.64 | 1.57 | 1.62 | 1.64 |
| | **Means** | **shrub** | **0.93** | **1.27** | **1.32** | **1.46** | **1.44** | **1.46** |
| | | **ecotone** | **0.98** | **1.36** | **1.37** | **1.50** | **1.47** | **1.51** |
| | | **grassland** | **1.07** | **1.28** | **1.46** | **1.43** | **1.47** | **1.46** |
| Loamy | Kernen | shrub | 0.52 | 0.83 | 0.99 | 1.07 | 1.14 | 1.16 |
| | | ecotone | 0.77 | 1.01 | 0.91 | 1.08 | 1.25 | 1.16 |
| | | grassland | 0.55 | 0.86 | 1.15 | 1.19 | 1.18 | 1.16 |
| | Abott | shrub | 0.49 | 0.79 | 1.11 | 1.28 | 1.37 | NA |
| | | ecotone | 0.44 | 0.84 | 1.40 | 1.39 | 1.33 | NA |
| | | grassland | 0.64 | 1.03 | 1.21 | 1.39 | 1.33 | NA |
| | Wilner | shrub | 0.58 | 0.82 | 0.99 | 0.89 | 0.99 | 0.96 |
| | | ecotone | 0.79 | 1.01 | 1.16 | 1.20 | 1.11 | 1.24 |
| | | grassland | 0.79 | 1.06 | 1.23 | 1.31 | 1.28 | 1.25 |
| | Matador | shrub | 0.73 | 0.95 | 0.92 | 1.09 | 1.07 | 1.13 |
| | | ecotone | 0.94 | 0.90 | 0.91 | 0.88 | 0.97 | 1.18 |
| | | grassland | 0.92 | 1.04 | 1.10 | 1.04 | 1.10 | 1.13 |
| | **Means** | **shrub** | **0.58** | **0.85** | **1.00** | **1.08** | **1.14** | **1.08** |
| | | **ecotone** | **0.74** | **0.94** | **1.10** | **1.14** | **1.17** | **1.19** |
| | | **grassland** | **0.72** | **1.00** | **1.17** | **1.23** | **1.22** | **1.18** |

### 2.3.4. Fine root biomass as affected by the grassland-shrub gradient, soil texture and soil depth

Fine root biomass was not significantly different along the grassland to shrub gradient at any depth increment or the whole soil profile ($P > 0.1$) (Table 2.6). The non-significant differences among community types decreased with increasing soil depth. Total fine root biomass in the profile averaged 0.7 kg m$^{-2}$. Fine root biomass was highest in the top 3 cm and decreased sharply with increasing depth (Table 2.7). The non-significant differences between community types also decreased with increasing soil depth.

Interactions between shrub community and soil texture were not significant at any soil depths. The effect of soil texture on fine root biomass was significant in the 20-30, 30-40, and 40-50 cm depths but not in the 0-20 increments (Tables 2.6).

**Table 2.6.** Means comparisons for the effects of soil texture and plant community type along the gradient from grassland to shrub on fine root biomass in the Prairie Ecozone of Saskatchewan.

| Comparison | | | -----0-3 cm ----- | | | --------3-10 cm------ | | | ---10-20 cm--- | | | --20-30 cm--- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E | P |
| | | | (mg cm$^{-3}$) | | | | | | | | | | | |
| Ec (Ecotone) | vs. | Sh (Shrub) | -1.82 | 1.59 | 0.50 | -0.18 | 0.42 | 0.91 | 0.02 | 0.13 | 0.98 | 0.01 | 0.10 | 0.99 |
| Gr (Grassland) | vs. | Sh | -2.07 | 1.59 | 0.41 | 0.30 | 0.42 | 0.76 | 0.10 | 0.13 | 0.72 | 0.12 | 0.10 | 0.44 |
| Gr | vs. | Ec | -0.24 | 1.59 | 0.99 | 0.48 | 0.42 | 0.51 | 0.08 | 0.13 | 0.82 | 0.11 | 0.10 | 0.51 |
| S (Sand) | vs. | L (Loam) | -0.06 | 1.33 | 0.97 | 0.44 | 0.34 | 0.21 | -0.11 | 0.10 | 0.31 | -0.24 | 0.07 | **0.00** |
| Sh x L | vs. | Sh x S | -3.10 | 2.30 | 0.74 | 0.13 | 0.60 | 1.00 | 0.23 | 0.18 | 0.82 | 0.30 | 0.10 | **0.07** |
| Ec x S | vs. | Sh x S | -4.20 | 2.10 | 0.38 | 0.12 | 0.57 | 1.00 | 0.16 | 0.17 | 0.94 | 0.10 | 0.10 | 0.87 |
| Gr x S | vs. | Sh x S | -3.90 | 2.10 | 0.47 | 0.76 | 0.57 | 0.76 | 0.12 | 0.17 | 0.98 | 0.10 | 0.10 | 0.77 |
| Ec x L | vs. | Sh x L | 1.20 | 2.40 | 1.00 | -0.55 | 0.63 | 0.95 | -0.15 | 0.19 | 0.97 | -0.10 | 0.10 | 0.90 |
| Gr x L | vs. | Sh x L | 0.20 | 2.40 | 1.00 | -0.28 | 0.63 | 1.00 | 0.08 | 0.19 | 1.00 | 0.10 | 0.10 | 0.96 |
| Ec x L | vs. | Ec x S | 2.30 | 2.30 | 0.90 | -0.54 | 0.60 | 0.94 | -0.09 | 0.18 | 1.00 | 0.10 | 0.10 | 0.97 |
| Gr x S | vs. | Ec x S | 0.40 | 2.10 | 1.00 | 0.64 | 0.57 | 0.86 | -0.04 | 0.17 | 1.00 | 0.00 | 0.10 | 1.00 |
| Gr x L | vs. | Ec x L | -1.00 | 2.40 | 1.00 | 0.28 | 0.63 | 1.00 | 0.23 | 0.19 | 0.85 | 0.20 | 0.10 | 0.44 |
| Gr x L | vs. | Gr x S | 1.00 | 2.30 | 1.00 | -0.91 | 0.60 | 0.67 | 0.18 | 0.18 | 0.92 | 0.30 | 0.10 | 0.14 |

[1] Difference in means between factors A and B.

**Table 2.4.** Continued

| Comparison | | | ----30-40 cm---- | | | ------40-50 cm------ | | | ----0-50 cm---- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ----------(mg cm$^{-3}$)---------- | | | | | | -------(kg m$^{-2}$)------ | | |
| Ec (Ecotone) | vs. | Sh (Shrub) | 0.07 | 0.08 | 0.71 | -0.03 | 0.08 | 0.90 | -0.06 | 0.08 | 0.74 |
| Gr (Grassland) | vs. | Sh | 0.14 | 0.08 | 0.21 | 0.10 | 0.08 | 0.41 | 0.00 | 0.08 | 1.00 |
| Gr | vs. | Ec | 0.08 | 0.08 | 0.63 | 0.13 | 0.08 | 0.21 | 0.06 | 0.08 | 0.74 |
| S (Sand) | vs. | L (Loam) | -0.16 | 0.06 | **0.02** | -0.16 | 0.06 | **0.01** | -0.04 | 0.06 | 0.54 |
| Sh x L | vs. | Sh x S | 0.20 | 0.11 | 0.46 | 0.10 | 0.10 | 0.92 | 0.01 | 0.11 | 1.00 |
| Ec x S | vs. | Sh x S | 0.12 | 0.10 | 0.84 | -0.06 | 0.09 | 0.99 | -0.08 | 0.11 | 0.97 |
| Gr x S | vs. | Sh x S | 0.14 | 0.10 | 0.74 | 0.04 | 0.09 | 1.00 | -0.02 | 0.11 | 1.00 |
| Ec x L | vs. | Sh x L | 0.00 | 0.11 | 1.00 | 0.00 | 0.10 | 1.00 | -0.03 | 0.12 | 1.00 |
| Gr x L | vs. | Sh x L | 0.15 | 0.11 | 0.78 | 0.18 | 0.10 | 0.55 | 0.03 | 0.12 | 1.00 |
| Ec x L | vs. | Ec x S | 0.08 | 0.11 | 0.97 | 0.16 | 0.10 | 0.62 | 0.06 | 0.11 | 0.99 |
| Gr x S | vs. | Ec x S | 0.02 | 0.10 | 1.00 | 0.10 | 0.09 | 0.88 | 0.06 | 0.11 | 0.99 |
| Gr x L | vs. | Ec x L | 0.15 | 0.11 | 0.78 | 0.18 | 0.10 | 0.55 | 0.05 | 0.12 | 1.00 |
| Gr x L | vs. | Gr x S | 0.21 | 0.11 | 0.41 | 0.23 | 0.10 | 0.22 | 0.05 | 0.11 | 1.00 |

**Table 2.7** Fine root biomass (FRB) along the gradient from grassland to shrub communities in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 3 shrub plots, 1 ecotone plot, and 2 grassland plots, respectively.

| | | | Soil depth (cm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Texture class | Site | Plot location | 0-50 | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | FRB(kg $m^{-2}$) | FRB (mg $cm^{-3}$) | | | | | |
| Sandy | Biddulph | Shrub | 0.6 | 8.1 | 2.9 | 0.6 | 0.4 | 0.2 | 0.2 |
| | | Ecotone | 0.8 | 11.5 | 3.8 | 0.9 | 0.4 | 0.2 | 0.1 |
| | | Grassland | 0.8 | 9.1 | 3.1 | 1.2 | 0.6 | 0.5 | 0.4 |
| | Rudy | Shrub | 0.6 | 10.3 | 1.6 | 0.5 | 0.5 | 0.2 | 0.2 |
| | | Ecotone | 0.3 | 3.1 | 0.4 | 0.9 | 0.4 | 0.5 | 0.2 |
| | | Grassland | 0.6 | 6.1 | 4.1 | 0.7 | 0.4 | 0.3 | 0.2 |
| | Montrose North | Shrub | 0.9 | 18.2 | 1.8 | 1.6 | 0.6 | 0.2 | 0.0 |
| | | Ecotone | 0.6 | 10.2 | 1.9 | 0.7 | 0.5 | 0.3 | 0.2 |
| | | Grassland | 0.6 | 7.2 | 2.2 | 0.9 | 0.6 | 0.5 | 0.3 |
| | Montrose South | Shrub | 0.7 | 11.2 | 1.9 | 0.7 | 0.3 | 0.5 | 0.5 |
| | | Ecotone | 0.6 | 7.0 | 1.8 | 1.2 | 0.7 | 0.4 | 0.4 |
| | | Grassland | 0.8 | 12.7 | 2.2 | 0.9 | 0.8 | 0.4 | 0.3 |
| | Coop | Shrub | 0.8 | 15.4 | 2.9 | 0.6 | 0.4 | 0.4 | 0.5 |
| | | Ecotone | 0.9 | 10.2 | 3.8 | 1.1 | 0.8 | 0.7 | 0.2 |
| | | Grassland | 0.7 | 8.7 | 3.3 | 0.9 | 0.5 | 0.5 | 0.4 |
| | **Means** | **Shrub** | **0.7** | **12.6** | **2.2** | **0.8** | **0.4** | **0.3** | **0.3** |
| | | **Ecotone** | **0.6** | **8.4** | **2.3** | **1.0** | **0.6** | **0.4** | **0.2** |
| | | **Grassland** | **0.7** | **8.8** | **3.0** | **0.9** | **0.6** | **0.4** | **0.3** |
| Loamy | Kernen | Shrub | 0.8 | 14.3 | 1.9 | 0.9 | 0.8 | 0.6 | 0.4 |
| | | Ecotone | 0.8 | 12.3 | 2.5 | 1.2 | 0.6 | 0.4 | 0.2 |
| | | Grassland | 0.8 | 10.7 | 1.8 | 1.0 | 1.1 | 0.8 | 0.6 |
| | Abott | Shrub | 0.7 | 10 | 2.6 | 0.8 | 0.7 | 0.3 | 0.4 |
| | | Ecotone | 0.4 | 5.9 | 1 | 0.6 | 0.5 | 0.4 | 0.4 |
| | | Grassland | 0.7 | 10.4 | 1.5 | 1.2 | 0.7 | 0.6 | 0.6 |
| | Wilner | Shrub | 0.7 | 6.7 | 2.5 | 1.4 | 0.9 | 0.5 | 0.3 |
| | | Ecotone | 0.9 | 14 | 1.4 | 1.0 | 1.0 | 0.8 | 0.6 |
| | | Grassland | 1.0 | 12.3 | 3.4 | 1.2 | 1.0 | 0.8 | 0.7 |
| | Matador | Shrub | 0.7 | 7.1 | 2.4 | 1.0 | 0.7 | 0.6 | 0.4 |
| | | Ecotone | 0.7 | 10.7 | 2.3 | 0.7 | 0.5 | 0.4 | 0.3 |
| | | Grassland | 0.5 | 5.5 | 1.6 | 1.0 | 0.7 | 0.4 | 0.3 |
| | **Means** | **Shrub** | **0.7** | **9.5** | **2.4** | **1.0** | **0.8** | **0.5** | **0.4** |
| | | **Ecotone** | **0.7** | **10.7** | **1.8** | **0.9** | **0.7** | **0.5** | **0.4** |
| | | **Grassland** | **0.8** | **9.7** | **2.1** | **1.1** | **0.9** | **0.7** | **0.6** |

### 2.3.5. Medium root biomass as affected by grassland-shrub gradient, soil texture and soil depth

Medium root biomass was not significantly affected by plant community type along the gradient from grassland to shrub in any depth increment or the whole profile ($P > 0.1$) (Table 2.8). Medium root biomass decreased with increasing depth, but unlike SOC and fine root biomass, the non-significant differences among communities did not have a clear trend from upper to lower soil profile (Tables 2.8, 2.9).

Medium root biomass was significantly affected by soil texture only at the 30-40 cm depth where medium root biomass was 0.18 g cm$^{-3}$ greater in loamy than sandy soils (Tables 2.8). The interactions between plant community and soil texture were significant for medium root biomass in the 0-3, 20-30, and 30-40 cm depths. However, no significant community or texture effect was found at the 0-3 cm depth using pairwise comparison. Medium root biomass was 0.68 mg cm$^{-3}$ greater in shrub than ecotone community at the 10-20 cm depth for loamy sites.

**Table 2.8.** Mean comparisons about the effects of soil texture and plant community type along the gradient from grassland to shrub on medium root biomass in the Prairie Ecozone of Saskatchewan.

| Comparison | | | ----0-3 cm ---- | | | ----3-10 cm---- | | | ---- 10-20 cm ---- | | | ----20-30 cm---- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | (mg cm$^{-3}$) | | | | | | | | | | | |
| Ec (Ecotone) | vs. | Sh (Shrub) | 0.23 | 0.46 | 0.87 | -0.24 | 0.24 | 0.58 | -0.30 | 0.17 | 0.19 | 0.23 | 0.46 | 0.87 |
| Gr (Grassland) | vs. | Sh | -0.04 | 0.46 | 0.99 | -0.33 | 0.24 | 0.37 | -0.13 | 0.17 | 0.70 | -0.04 | 0.46 | 0.99 |
| Gr | vs. | Ec | -0.28 | 0.46 | 0.82 | -0.09 | 0.24 | 0.93 | 0.17 | 1.01 | 0.58 | -0.28 | 0.46 | 0.82 |
| S (Sand) | vs. | L (Loam) | 0.38 | 0.37 | 0.31 | -0.13 | 0.20 | 0.52 | -0.16 | 0.14 | 0.27 | 0.38 | 0.37 | 0.31 |
| Sh x L | vs. | Sh x S | -0.02 | 0.68 | 1.00 | 0.42 | 0.36 | 0.85 | 0.56 | 0.22 | 0.16 | -0.02 | 0.68 | 1.00 |
| Ec x S | vs. | Sh x S | 0.50 | 0.64 | 0.97 | -0.04 | 0.34 | 1.00 | 0.00 | 0.21 | 1.00 | 0.50 | 0.64 | 0.97 |
| Gr x S | vs. | Sh x S | 0.18 | 0.64 | 1.00 | -0.16 | 0.34 | 1.00 | 0.10 | 0.21 | 1.00 | 0.18 | 0.64 | 1.00 |
| Ec x L | vs. | Sh x L | -0.10 | 0.72 | 1.00 | -0.50 | 0.38 | 0.77 | -0.68 | 0.23 | **0.08** | -0.10 | 0.72 | 1.00 |
| Gr x L | vs. | Sh x L | -0.33 | 0.72 | 1.00 | -0.55 | 0.38 | 0.70 | -0.43 | 0.23 | 0.46 | -0.33 | 0.72 | 1.00 |
| Ec x L | vs. | Ec x S | -0.62 | 0.68 | 0.94 | -0.05 | 0.36 | 1.00 | -0.12 | 0.22 | 0.99 | -0.62 | 0.68 | 0.94 |
| Gr x S | vs. | Ec x S | -0.32 | 0.64 | 1.00 | -0.12 | 0.34 | 1.00 | 0.10 | 0.21 | 1.00 | -0.32 | 0.64 | 1.00 |
| Gr x L | vs. | Ec x L | -0.23 | 0.72 | 1.00 | -0.05 | 0.38 | 1.00 | 0.25 | 0.23 | 0.88 | -0.23 | 0.72 | 1.00 |
| Gr x L | vs. | Gr x S | -0.52 | 0.68 | 0.97 | 0.03 | 0.36 | 1.00 | 0.03 | 0.22 | 1.00 | -0.52 | 0.68 | 0.97 |

[1] Difference in means between factors A and B.

**Table 2.8.** Continued

| Comparison | | | ---30-40 cm--- | | | ---40-50 cm--- | | | ---0-50 cm--- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ($\mathrm{mg\ cm^{-3}}$) | | | | | | ($\mathrm{kg\ m^{-2}}$) | | |
| Ec (Ecotone) | vs. | Sh (Shrub) | -0.12 | 0.1 | 0.41 | -0.12 | 0.08 | 0.34 | 0.14 | 0.11 | 0.39 |
| Gr (Grassland) | vs. | Sh | -0.06 | 0.1 | 0.83 | -0.07 | 0.08 | 0.72 | 0.06 | 0.11 | 0.87 |
| Gr | vs. | Ec | 0.07 | 0.1 | 0.76 | 0.06 | 0.08 | 0.79 | -0.09 | 0.11 | 0.69 |
| S (Sand) | vs. | L (Loam) | -0.18 | 0.1 | **0.02** | -0.07 | 0.07 | 0.30 | 0.12 | 0.09 | 0.18 |
| Sh x L | vs. | Sh x S | 0.42 | 0.1 | **0.01** | 0.10 | 0.12 | 0.97 | -0.05 | 0.16 | 1.00 |
| Ec x S | vs. | Sh x S | 0.06 | 0.1 | 0.99 | -0.06 | 0.11 | 0.99 | 0.22 | 0.15 | 0.67 |
| Gr x S | vs. | Sh x S | 0.08 | 0.1 | 0.97 | -0.10 | 0.11 | 0.95 | 0.08 | 0.15 | 0.99 |
| Ec x L | vs. | Sh x L | -0.35 | 0.1 | **0.06** | -0.20 | 0.13 | 0.63 | 0.05 | 0.16 | 1.00 |
| Gr x L | vs. | Sh x L | -0.23 | 0.1 | 0.39 | -0.03 | 0.13 | 1.00 | 0.03 | 0.16 | 1.00 |
| Ec x L | vs. | Ec x S | 0.01 | 0.1 | 1.00 | -0.05 | 0.12 | 1.00 | -0.22 | 0.16 | 0.74 |
| Gr x S | vs. | Ec x S | 0.02 | 0.1 | 1.00 | -0.04 | 0.11 | 1.00 | -0.14 | 0.15 | 0.93 |
| Gr x L | vs. | Ec x L | 0.13 | 0.1 | 0.88 | 0.18 | 0.13 | 0.75 | -0.03 | 0.16 | 1.00 |
| Gr x L | vs. | Gr x S | 0.12 | 0.1 | 0.89 | 0.17 | 0.12 | 0.73 | -0.10 | 0.16 | 0.99 |

**Table 2.9.** Medium root biomass (MRB) along the gradient from grassland to shrub communities in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 3 shrub plots, 1 ecotone plot, and 2 grassland plots respectively.

| | | | Soil depth (cm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Texture class | Site | Plot location | 0-50 | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | MRB (kg m$^{-2}$) | MRB (mg cm$^{-3}$) | | | | | |
| Sandy | Biddulph | Shrub | 0.8 | 6.6 | 2.9 | 1.7 | 1.1 | 0.4 | 0.4 |
| | | Ecotone | 0.9 | 18.3 | 2.4 | 1.3 | 0.5 | 0.3 | 0.1 |
| | | Grassland | 0.8 | 9.0 | 3.3 | 1.4 | 0.7 | 0.6 | 0.4 |
| | Rudy | Shrub | 1.4 | 23.2 | 4.6 | 2.0 | 0.8 | 0.3 | 0.4 |
| | | Ecotone | 1.6 | 28.5 | 5.6 | 1.6 | 1.0 | 0.5 | 0.4 |
| | | Grassland | 1.1 | 16.9 | 4.0 | 1.6 | 0.8 | 0.3 | 0.2 |
| | Montrose North | Shrub | 1.0 | 15.9 | 4.3 | 1.3 | 0.4 | 0.1 | 0.1 |
| | | Ecotone | 1.1 | 19.4 | 3.7 | 1.5 | 0.5 | 0.3 | 0.2 |
| | | Grassland | 1.0 | 23.1 | 2.1 | 0.4 | 0.4 | 0.2 | 0.2 |
| | Montrose South | Shrub | 0.7 | 9.6 | 1.9 | 1.2 | 0.4 | 0.4 | 0.8 |
| | | Ecotone | 1.2 | 24.0 | 2.7 | 1.2 | 0.5 | 0.3 | 0.6 |
| | | Grassland | 1.1 | 17.0 | 4.0 | 1.7 | 0.8 | 0.4 | 0.3 |
| | Coop | Shrub | 0.7 | 10.4 | 3.0 | 0.6 | 0.4 | 0.2 | 0.2 |
| | | Ecotone | 0.9 | 10.8 | 4.8 | 1.0 | 0.6 | 0.3 | 0.3 |
| | | Grassland | 1.0 | 14.6 | 4.2 | 0.9 | 0.9 | 0.3 | 0.3 |
| | **Means** | **Shrub** | **0.9** | **13.1** | **3.3** | **1.4** | **0.6** | **0.3** | **0.4** |
| | | **Ecotone** | **1.1** | **20.2** | **3.8** | **1.3** | **0.6** | **0.3** | **0.3** |
| | | **Grassland** | **1.0** | **16.1** | **3.5** | **1.2** | **0.7** | **0.4** | **0.3** |
| Loamy | Kernen | Shrub | 0.7 | 8.0 | 2.4 | 1.1 | 0.7 | 0.5 | 0.4 |
| | | Ecotone | 0.7 | 11.5 | 2.4 | 1.0 | 0.4 | 0.6 | 0.4 |
| | | Grassland | 1.0 | 12.7 | 3.2 | 1.5 | 1.0 | 0.7 | 0.8 |
| | Abbott | Shrub | 1.0 | 14.2 | 3.6 | 1.5 | 0.9 | 0.5 | 0.4 |
| | | Ecotone | 1.2 | 22.9 | 4.3 | 1.2 | 0.3 | 0.3 | 0.2 |
| | | Grassland | 0.7 | 9.8 | 2.0 | 1.1 | 0.6 | 0.3 | 0.3 |
| | Wilner | Shrub | 1.0 | 2.5 | 4.2 | 3.2 | 2.1 | 1.0 | 0.5 |
| | | Ecotone | 1.0 | 14.3 | 3.8 | 1.9 | 0.8 | 0.3 | 0.3 |
| | | Grassland | 1.2 | 19.8 | 3.8 | 1.3 | 0.9 | 0.5 | 0.4 |
| | Matador | Shrub | 0.8 | 6.4 | 3.1 | 1.3 | 1.0 | 0.8 | 0.6 |
| | | Ecotone | 0.8 | 13.4 | 2.4 | 1.0 | 0.5 | 0.2 | 0.2 |
| | | Grassland | 0.7 | 9.5 | 3.0 | 1.0 | 0.5 | 0.4 | 0.3 |
| | **Means** | **Shrub** | **0.9** | **7.8** | **3.3** | **1.8** | **1.2** | **0.7** | **0.5** |
| | | **Ecotone** | **0.9** | **15.5** | **3.2** | **1.3** | **0.5** | **0.4** | **0.3** |
| | | **Grassland** | **0.9** | **13.0** | **3.0** | **1.2** | **0.8** | **0.5** | **0.5** |

### 2.3.6. Large root biomass as affected by grassland-shrub gradient, soil texture and soil depth

Large root biomass was significantly affected by community type at most depth increments and for the whole profile (Table 2.10). Large root biomass was higher in the shrub community than the ecotone and grassland at most depth increments except the 20-30 cm depth. Ecotone had a greater large root biomass than grassland only at 3-10 cm and the soil profile as a whole. Overall, the 3-10 cm depth seemed to contain more large root biomass per volume soil than any other depth increment (Table 2.11). Interactions between shrub community and soil texture were not significant for large root biomass at any soil depths and large root biomass was not significantly affected by soil texture at any soil depths.

**Table 2.10.** Mean comparisons about the effects of soil texture and plant community type along the gradient from grassland to shrub on large root biomass in the Prairie Ecozone of Saskatchewan.

| Comparison | | | -----0-3 cm ----- | | | ------3-10 cm------ | | | ---10-20 cm-- | | | --20-30 cm-- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | -(mg cm$^{-3}$)- | | | | | | | | | | | |
| Ec (Ecotone) | vs. | Sh (Shrub) | -3.67 | 1.43 | **0.04** | -2.98 | 0.93 | **0.01** | -2.42 | 0.65 | **0.00** | -0.44 | 0.45 | 0.59 |
| Gr (Grassland) | vs. | Sh | -4.69 | 1.43 | **0.01** | -6.08 | 0.93 | **0.00** | -3.19 | 0.65 | **0.00** | -0.93 | 0.45 | 0.12 |
| Gr | vs. | Ec | -1.02 | 1.43 | 0.76 | -3.10 | 0.93 | **0.01** | -0.77 | 0.65 | 0.48 | -0.49 | 0.45 | 0.53 |
| S (Sand) | vs. | L (Loam) | 1.59 | 1.37 | 0.26 | 0.21 | 1.25 | 0.87 | 0.23 | 0.76 | 0.77 | -0.17 | 0.39 | 0.67 |
| Sh x L | vs. | Sh x S | -0.20 | 2.10 | 1.00 | 0.52 | 1.40 | 1.00 | 0.22 | 0.98 | 1.00 | 0.48 | 0.67 | 0.98 |
| Ec x S | vs. | Sh x S | -2.50 | 1.90 | 0.79 | -2.38 | 1.32 | 0.48 | -2.14 | 0.93 | 0.24 | -0.32 | 0.63 | 1.00 |
| Gr x S | vs. | Sh x S | -4.10 | 1.90 | 0.33 | -5.70 | 1.32 | **0.00** | -2.88 | 0.93 | **0.05** | -0.64 | 0.63 | 0.91 |
| Ec x L | vs. | Sh x L | -5.10 | 2.20 | 0.21 | -3.73 | 1.47 | 0.16 | -2.78 | 1.04 | 0.12 | -0.60 | 0.71 | 0.96 |
| Gr x L | vs. | Sh x L | -5.50 | 2.20 | 0.16 | -6.55 | 1.47 | **0.00** | -3.58 | 1.04 | 0.03 | -1.30 | 0.71 | 0.47 |
| Ec x L | vs. | Ec x S | -2.90 | 2.10 | 0.73 | -0.83 | 1.40 | 0.99 | -0.42 | 0.98 | 1.00 | 0.20 | 0.67 | 1.00 |
| Gr x S | vs. | Ec x S | -1.60 | 1.90 | 0.96 | -3.32 | 1.32 | 0.16 | -0.74 | 0.93 | 0.96 | -0.32 | 0.63 | 1.00 |
| Gr x L | vs. | Ec x L | -0.40 | 2.20 | 1.00 | -2.83 | 1.47 | 0.42 | -0.80 | 1.04 | 0.97 | -0.70 | 0.71 | 0.92 |
| Gr x L | vs. | Gr x S | -1.70 | 2.10 | 0.96 | -0.33 | 1.40 | 1.00 | -0.48 | 0.98 | 1.00 | -0.18 | 0.67 | 1.00 |

[1] Difference in means between factors A and B.

**Table 2.10.** Continued.

| Comparison | | | ---30-40 cm ---- | | | -----40-50 cm ----- | | | ---0-50 cm --- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ---------------(mg cm$^{-3}$)------------------- | | | | | | ------(kg m$^{-2}$)------- | | |
| Ec (Ecotone) | vs. | Sh (Shrub) | -0.34 | 0.13 | **0.04** | -0.14 | 0.05 | **0.01** | -0.64 | 0.17 | **0.00** |
| Gr (Grassland) | vs. | Sh | -0.36 | 0.13 | **0.03** | -0.16 | 0.05 | **0.01** | -1.04 | 0.17 | **0.00** |
| Gr | vs. | Ec | -0.01 | 0.13 | 1.00 | -0.01 | 0.05 | 0.97 | -0.40 | 0.17 | **0.07** |
| S (Sand) | vs. | L (Loam) | -0.13 | 0.12 | 0.32 | -0.04 | 0.05 | 0.46 | 0.06 | 0.22 | 0.78 |
| Sh x L | vs. | Sh x S | 0.35 | 0.19 | 0.44 | 0.08 | 0.07 | 0.84 | 0.14 | 0.26 | 0.99 |
| Ec x S | vs. | Sh x S | -0.20 | 0.18 | 0.86 | -0.12 | 0.06 | 0.44 | -0.50 | 0.24 | 0.34 |
| Gr x S | vs. | Sh x S | -0.20 | 0.18 | 0.86 | -0.12 | 0.06 | 0.44 | -0.92 | 0.24 | 0.01 |
| Ec x L | vs. | Sh x L | -0.53 | 0.20 | 0.12 | -0.18 | 0.07 | 0.19 | -0.83 | 0.27 | 0.06 |
| Gr x L | vs. | Sh x L | -0.55 | 0.20 | **0.10** | -0.20 | 0.07 | **0.10** | -1.20 | 0.27 | 0.00 |
| Ec x L | vs. | Ec x S | 0.03 | 0.19 | 1.00 | 0.03 | 0.07 | 1.00 | -0.19 | 0.26 | 0.98 |
| Gr x S | vs. | Ec x S | 0.00 | 0.18 | 1.00 | 0.00 | 0.06 | 1.00 | -0.42 | 0.24 | 0.52 |
| Gr x L | vs. | Ec x L | -0.03 | 0.20 | 1.00 | -0.03 | 0.07 | 1.00 | -0.38 | 0.27 | 0.73 |
| Gr x L | vs. | Gr x S | 0.00 | 0.19 | 1.00 | 0.00 | 0.07 | 1.00 | -0.14 | 0.26 | 0.99 |

**Table 2.11.** Large root biomass (LRB) along the gradient from grassland to shrub communities in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 3 shrub plots, 1 ecotone plot, and 2 grassland plots respectively.

| | | | Soil depth (cm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Texture class | Site | Plot location | 0-50 | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | LRB (kg m$^{-2}$) | Large roots (mg cm$^{-3}$) | | | | | |
| Sandy | Biddulph | Shrub | 0.9 | 1.7 | 2.8 | 3.4 | 2.1 | 0.3 | 0.3 |
| | | Ecotone | 0.4 | 0.0 | 0.6 | 3.1 | 0.3 | 0.0 | 0.0 |
| | | Grassland | 0.2 | 0.0 | 0.4 | 1.0 | 0.3 | 0.0 | 0.0 |
| | Rudy | Shrub | 0.7 | 0.7 | 3.3 | 3.6 | 0.6 | 0.0 | 0.0 |
| | | Ecotone | 0.5 | 2.1 | 4.7 | 0.8 | 0.1 | 0.0 | 0.0 |
| | | Grassland | 0.0 | 0.4 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Montrose North | Shrub | 1.3 | 3.4 | 9.1 | 4.6 | 0.7 | 0.3 | 0.3 |
| | | Ecotone | 0.6 | 4.0 | 5.1 | 0.5 | 0.4 | 0.0 | 0.0 |
| | | Grassland | 0.3 | 7.9 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 |
| | Montrose South | Shrub | 1.1 | 12.7 | 6.9 | 2.1 | 0.4 | 0.0 | 0.0 |
| | | Ecotone | 0.7 | 6.5 | 4.6 | 1.1 | 0.5 | 0.0 | 0.0 |
| | | Grassland | 0.2 | 0.0 | 1.2 | 1.1 | 0.6 | 0.0 | 0.0 |
| | Coop | Shrub | 1.3 | 10.1 | 8.8 | 3.1 | 0.3 | 0.4 | 0.0 |
| | | Ecotone | 0.6 | 3.5 | 4.0 | 0.6 | 1.2 | 0.0 | 0.0 |
| | | Grassland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | **Means** | **Shrub** | **1.1** | **5.7** | **6.2** | **3.4** | **0.8** | **0.2** | **0.1** |
| | | **Ecotone** | **0.6** | **3.2** | **3.8** | **1.2** | **0.5** | **0.0** | **0.0** |
| | | **Grassland** | **0.1** | **1.7** | **0.5** | **0.5** | **0.2** | **0.0** | **0.0** |
| Loamy | Kernen | Shrub | 1.0 | 4.6 | 7.8 | 2.0 | 0.4 | 0.2 | 0.1 |
| | | Ecotone | 0.2 | 0.0 | 2.4 | 0.5 | 0.0 | 0.1 | 0.1 |
| | | Grassland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Abott | Shrub | 1.1 | 4.1 | 6.7 | 4.4 | 0.5 | 0.2 | 0.4 |
| | | Ecotone | 0.2 | 0.0 | 2.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | Grassland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Wiiner | Shrub | 2.4 | 7.9 | 10.2 | 7.8 | 4.3 | 1.6 | 0.3 |
| | | Ecotone | 0.9 | 0.0 | 5.1 | 2.3 | 2.8 | 0.0 | 0.0 |
| | | Grassland | 0.0 | 0.0 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Matador | Shrub | 0.3 | 5.3 | 2.1 | 0.1 | 0.0 | 0.2 | 0.0 |
| | | Ecotone | 0.2 | 1.4 | 2.1 | 0.4 | 0.0 | 0.0 | 0.0 |
| | | Grassland | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | **Means** | **Shrub** | **1.2** | **5.5** | **6.7** | **3.6** | **1.3** | **0.6** | **0.2** |
| | | **Ecotone** | **0.4** | **0.4** | **3.0** | **0.8** | **0.7** | **0.0** | **0.0** |
| | | **Grassland** | **0.0** | **0.0** | **0.2** | **0.0** | **0.0** | **0.0** | **0.0** |

### 2.3.7. Aboveground biomass as affected by the grassland-shrub gradient and soil texture

Herbaceous, litter, shrub, and total biomass was significantly affected by community type along the grassland to shrub gradient ($P \leq 0.1$) but not by soil texture (Tables 2.12). Herbaceous biomass decreased and shrub biomass increased along the gradient from grassland to shrub. Litter and total biomass was higher in the shrub community than the ecotone and grassland communities, but there was no significant differences between ecotone and grassland in litter or total biomass. Interactions between plant community and soil texture were not significant for any of the aboveground biomass components.

**Table 2.12.** Mean comparisons about the effects of soil texture and plant community type along the gradient from grassland to shrub on herbaceous, litter, shrub, and total biomass in the Prairie Ecozone of Saskatchewan.

| Comparison | | Herbaceous biomass | | | ---Litter biomass--- | | | ---Shrub biomass-- | | | ---Total biomass--- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | ---(g $m^{-2}$)--- | | | | | | | | | | | |
| Ec Ecotonnhe) | Vs. Sh (Shrub) | 53 | 16.9 | **0.01** | -785 | 255 | **0.01** | -522 | 82 | **0.00** | -1254 | 298 | **0.00** |
| Gr (Grassland) | Vs. Sh | 96 | 16.9 | **0.00** | -838 | 255 | **0.01** | -738 | 82 | **0.00** | -1480 | 298 | **0.00** |
| Gr | Vs. Ec | 43 | 16.9 | **0.05** | -53 | 255 | 0.98 | -216 | 82 | **0.04** | -226 | 298 | 0.73 |
| S (Sand) | Vs. L (Loam) | -8 | 20.8 | 0.69 | -267 | 251 | 0.30 | 44 | 141 | 0.76 | -231 | 352 | 0.52 |
| Sh x L | Vs. Sh x S | -10 | 25.0 | 1.00 | 590 | 364 | 0.59 | -90 | 124 | 0.98 | 490 | 439 | 0.87 |
| Ec x S | Vs. Sh x S | 42 | 23.6 | 0.49 | -542 | 343 | 0.62 | -547 | 116 | **0.00** | -1046 | 414 | 0.16 |
| Gr x S | Vs. Sh x S | 82 | 23.6 | **0.02** | -650 | 343 | 0.43 | -775 | 116 | **0.00** | -1342 | 414 | **0.04** |
| Ec x L | Vs. Sh x L | 67 | 26.4 | 0.16 | -1089 | 383 | **0.09** | -492 | 130 | **0.01** | -1514 | 463 | **0.04** |
| Gr x L | Vs. Sh x L | 113 | 26.4 | **0.00** | -1072 | 383 | **0.10** | -693 | 130 | **0.00** | -1652 | 463 | **0.02** |
| Ec x L | Vs. Ec x S | 15 | 25.0 | 0.99 | 43 | 364 | 1.00 | -35 | 124 | 1.00 | 22 | 439 | 1.00 |
| Gr x S | Vs. Ec x S | 40 | 23.6 | 0.55 | -108 | 343 | 1.00 | -228 | 116 | 0.40 | -296 | 414 | 0.98 |
| Gr x L | Vs. Ec x L | 46 | 26.4 | 0.52 | 17 | 383 | 1.00 | -201 | 130 | 0.64 | -138 | 463 | 1.00 |
| Gr x L | vs. Gr x S | 21 | 25.0 | 0.96 | 167 | 364 | 1.00 | -8 | 124 | 1.00 | 180 | 439 | 1.00 |

[1] Difference means between factors A and B.

**Table 2.13.** Aboveground biomass along the gradient from grassland to shrub communities in the Prairie Ecozone of Saskatchewan. Values are means of 8 subsamples from 3 shrub plots, 1 ecotone plot, and 2 grassland plots respectively.

| Site | Plot location | Herbaceous | Litter | Shrub | Total |
|---|---|---|---|---|---|
| | | Biomass ($g\ m^{-2}$) | | | |
| Biddulph | Shrub | 58 | 647 | 621 | 1326 |
| | Ecotone | 119 | 59 | 155 | 333 |
| | Grassland | 205 | 207 | 46 | 458 |
| Rudy | Shrub | 67 | 566 | 684 | 1317 |
| | Ecotone | 113 | 103 | 141 | 357 |
| | Grassland | 110 | 35 | 0 | 145 |
| Montrose North | Shrub | 63 | 551 | 550 | 1163 |
| | Ecotone | 34 | 221 | 365 | 619 |
| | Grassland | 107 | 45 | 0 | 153 |
| Montrose South | Shrub | 19 | 1174 | 1278 | 2471 |
| | Ecotone | 69 | 415 | 342 | 826 |
| | Grassland | 95 | 152 | 6 | 252 |
| Coop | Shrub | 38 | 1005 | 793 | 1837 |
| | Ecotone | 122 | 437 | 189 | 748 |
| | Grassland | 140 | 255 | 0 | 395 |
| **Means** | **Shrub** | **49** | **789** | **785** | **1623** |
| | **Ecotone** | **91** | **247** | **238** | **577** |
| | **Grassland** | **131** | **139** | **10** | **281** |
| Kernen | Shrub | 56 | 1083 | 549 | 1687 |
| | Ecotone | 121 | 380 | 384 | 885 |
| | Grassland | 205 | 499 | 0 | 705 |
| Abott | Shrub | 57 | 431 | 844 | 1333 |
| | Ecotone | 140 | 225 | 142 | 507 |
| | Grassland | 186 | 262 | 0 | 448 |
| Wilner | Shrub | 0 | 3381 | 1037 | 4418 |
| | Ecotone | 90 | 175 | 201 | 466 |
| | Grassland | 85 | 91 | 11 | 187 |
| Matador | Shrub | 43 | 619 | 351 | 1013 |
| | Ecotone | 73 | 378 | 87 | 538 |
| | Grassland | 132 | 372 | 0 | 504 |
| **Means** | **Shrub** | **39** | **1379** | **695** | **2113** |
| | **Ecotone** | **106** | **290** | **204** | **599** |
| | **Grassland** | **152** | **306** | **3** | **461** |

## 2.4. Discussion

Soil organic matter averaged 8.4 kg $m^{-2}$ among the 9 study sites, which was much higher than total root biomass (2.4 kg $m^{-2}$), total herbaceous and shrub biomass (0.8 kg $m^{-2}$), litter biomass (0.5 kg $m^{-2}$), or their combination. This indicates that SOC is the most important carbon pool in the Mixed Prairie. Increases in SOC along the gradient from grassland to shrub communities were less than 5%, which was not significant and lower than those reported in other grasslands (Barth and Klemmedson 1978, Hibbard et al. 2001, Jackson et al. 2002, Hudak et al. (2003). Bulk density, however, decreased from grassland to shrub communities, indicating that shrub invasion has altered the soil physical properties. Other factors, such as site conditions (wet vs. dry) and species of woody plants may affect SOC interactively. For examples, most of the above mentioned studies involved taller shrub and trees and some which are legumes, which may function differently in carbon cycling from the relatively low snowberry found in our study sites. In addition, Jackson et al. (2002) found that relatively dry sites (> 200 mm $year^{-1}$) gained SOC while wetter sites (< 1100 mm $year^{-1}$) lost SOC following invasion of woody species, such as mesquite, creosote, and juniper into a variety of grassland types in New Mexico, Texas, and Colorado.

Not surprisingly, shrub cover and biomass increased and herbaceous biomass decreased along the gradient from grassland to shrub communities. Litter cover was also higher in the shrub community than the ecotone and grassland communities, possibly due to the higher biomass production in the former. Large root biomass but not medium and small root biomass was higher in the shrub community than the others. This as well as the lack of significant differences in SOC among community types indicate that changes in above-ground carbon sequestration are more rapid than that in belowground, and both components should be considered in evaluating site potential for carbon sequestration.

Results of the present study indicate that soil texture plays a much greater role governing SOC than plant community composition in the Mixed Prairie, with loamy soils having greater SOC than sandy soils. Previous studies also found that SOC is higher in soils with fine texture relative to coarse texture soils (Burke et al. 1989, Bosatta and Agren 1997, Hudak et al. 2003, Galantini et al. 2004). Explanations for the positive relationship between clay and silt and SOC include physical protection of organic carbon fractions and formation of organomineral complexes (Galantini et al. 2004) and lower decomposition rates in clayey soils relative to sandy soils (van Veen et al. 1985).

Loamy soils also had a greater bulk density than sandy soils. But fine root biomass was higher in loamy soils than sandy soils only at deeper depth, indicating that plants at loamy sites can expand and explore soil water deeper in the soil profile than that in sandy soils. Medium root biomass was higher in loamy than sandy soils only at the 30-40 cm depth, while large root biomass and aboveground biomass did not vary significantly between soil texture types. Therefore, the effect of soil texture on carbon sequestration is best reflected in SOC and fine and medium root biomass, but not in large root biomass or aboveground biomass.

## Part III: Effect of Cattle Grazing on Biomass Production and Soil Carbon in the Mixed Prairie of Saskatchewan.

### 3.1 Introduction

Livestock grazing has potential to indirectly alter the soil carbon balance by impacting the physical, chemical, and biological processes that regulate organic carbon. Proper grazing management can increase SOC on rangelands (Schuman et al. 2002) while overgrazing can reduce C input from litter, increase soil temperature, alter microbial activity and decomposition, and increase the frequency of wet-dry cycles (Abril and Bucher 2001). Abril and Bucher (2001) reported that overgrazing in Argentinean subtropical woodland decreased SOC and cessation of cattle grazing resulted in C gain. These results are supported by Conant et al. (2001) who conducted a literature review on the effect of management on soil carbon and concluded that soil C in overgrazed sites decreased relative to moderately grazed sites. The effects of grazing management on SOC are variable and Conant et al. (2001)that the majority of studies showing grazing increased soil C were from warm dry regions. Annual SOC increase was 7.7 % for studies conducted in areas with a long history of grazing while sites with a relatively short grazing history lost an average of 1.8%.

A study from the Northern Great Plains indicates that ungrazed grassland consistently contained greater SOC than grazed grassland (Bauer et al. 1987) while data from other grasslands show grazing does not significantly alter SOC (Milchunas and Lauenroth 1993, Mathews et al. 1994, and Manley et al. 1995). Manley et. al (1995) conducted studies in Mixed Prairie in Wyoming and concluded that SOC in the top 7.6 cm of soil was lower ($P \leq 0.10$) in the exclosure than in all grazing treatments which included season-long light stocking rate, rotationally deferred, short-duration rotation, and continuous season-long (the latter three grazing treatments were applied at a heavy stocking rate). Frank et al. (1995) concluded that heavy grazing did not effect SOC realtive to control but moderate grazing reduced SOC compared to the control. They speculated that carbon removal by grazing animals may be the cause of this response while an increase in the dense shallow roots of blue grama (*Bouteloua gracilis*) in heavily grazed treatment likely accounted for maintenance of SOC relative to control. Smoliak et al. (1971) concluded that total carbon, alcohol/benzene extractable carbon, and alkaline-soluble carbon increased following 19 years of heavy grazing by sheep relative to light or no grazing in Alberta. They also speculated that the change in amount and kind of roots that accompanied a shift in species composition in heavily grazed areas is the reason for the increased C. Dormaar and Willms (1990), and Dormaar et al. (1984) also reported the total carbon and concentration of carbon increased following grazing caused by replacement species such as needle-and-thread (*Hesperostipa comata*) by the shallow-rooted blue grama.

Alternatively, Schuman et al. (1999) concluded that twelve years of heavy grazing on previously ungrazed Mixed Prairie in Wyoming did not altersoil C in the 0-60 cm profile relative to light grazing. This lack of effect on SOC occurred despite decreased peak standing crop and increased cover of blue grama in heavily grazed sites . Henderson et al. (2004), also found that grazing does not affect SOC despite greater vegetation and litter biomass in ungrazed areas than in grazed areas. They therefore concluded management practices that maintain range in good to poor condition may be consistent with maintaining SOC in Northern Great Plains. Potter et al. (2001) studied the effect of stocking rate on SOC in 2 soil types and concluded SOC decreased as stocking rate increased in one soil type while SOC was similar in grazed and ungrazed treatments for another soil type. The soil where SOC decreased with increasing stocking rate had greater sand content and lower SOC in the control relative to the second soil type where grazing treatment effects were not detected. It therefore appears that SOC response to grazing may be dependent on site factors such as soil texture and initial SOC content. Spatial and temporal variability of climate, soil characteristics, past disturbance history, and other site and environmental conditions may also influence the response of SOC to grazing.

The objective of this study is to determine if livestock grazing affects the amount of SOC in the Prairie Ecozone of Saskatchewan. The hypotheses that grazing has no effect on SOC, and aboveground, root and litter biomass, were tested. The hypothesis that grazing effects on SOC are dependent on soil texture was also tested.

## 3.2 Materials and Methods

### 3.2.1 Site selection and description

Nine paired sites were selected for the grazing study (Table 3.1). Moderately to heavily grazed grasslands in fair range condition and ungrazed grassland in good to excellent condition were selected. (Abouguendia 1990). After locating a suitable ungrazed or lightly site, a moderately or heavily grazed site within 2 km was located for comparison. The grazed sites were heavily grazed for more than 10 years prior to 2003. Livestock were not withheld from grazed study sites during or prior to data collection.

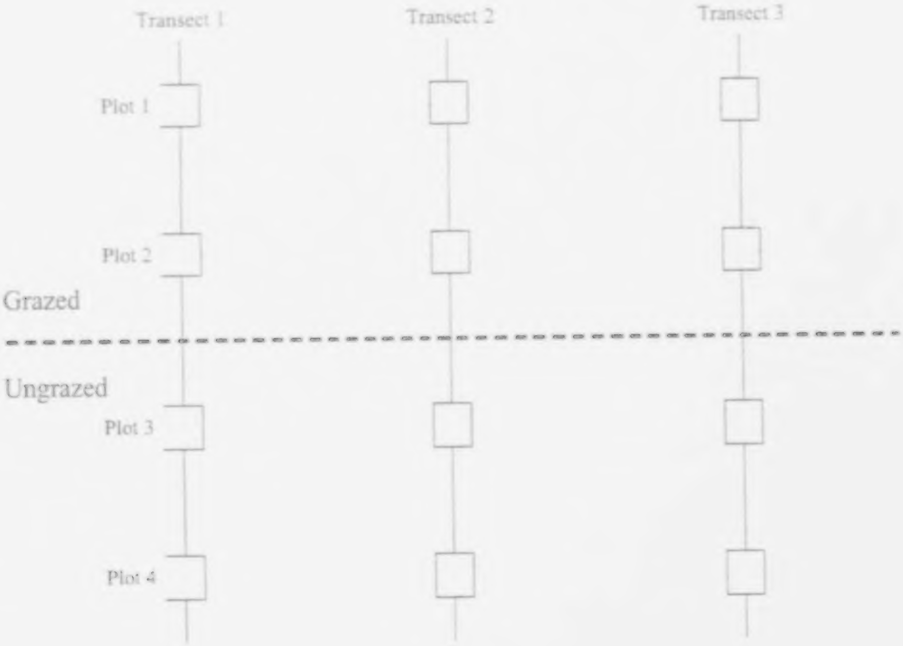

**Figure 3.1.** Diagram of the transect and plot layout at one site for studying the effect of livestock grazing on plant species composition, standing crop, and soil organic carbon.

### 3.2.2 Experimental design

Three transects were established at each study site and four, 2 x 2 m plots were located along each transect (Figure 3.1). Two plots per transect were located in an ungrazed area and 2 were located in a grazed area. Plots within each treatment were located approximately 15 m apart. All data were collected within the 2 x 2 m study plots. The nine sites were used as replications for this study. Data were collected in six grazed and six ungrazed 2 x 2 m plots at each study site. Distance between plots within grazed and ungrazed treatments ranged from approximately 10 to 50 m.

### 3.2.3 Data collection and analysis

Dependent variables measured or estimated included aboveground plant biomass, species composition, ground cover, soil organic carbon, root biomass, soil texture and bulk density. Data were collected and analyzed in August 2003 or 2004 as described in the previous chaper.

**Table 3.1.** Descriptions of 9 sites in central and southern Saskatchewan for the grazing study.

| Site and study year | Soil texture, Landscape type, and Ecoregion | Dominant graminoids | Township | Grazing history |
|---|---|---|---|---|
| Matador North 2003 | Loamy<br>Lacustrine plain<br>Mixed Grassland | Northern wheatgrass[1]<br>Junegrass[2]<br>Green needlegrass[3] | Tp20 R14 W3 | Ungrazed plots protected from livestock for over 15 years.<br>Grazed plots heavily grazed for over 15 years |
| Matador South 2003 | Loamy<br>Lacustrine plain<br>Mixed Grassland | Green needlegrass<br>Northern wheatgrass<br>Blue grama[4] | Tp20 R14 W3 (1 km south of Matador North) | Ungrazed plots protected from livestock for over 15 years.<br>Grazed plot heavily grazed for over 15 years |
| Biddulph 2003 | Sandy<br>Fluvial plain<br>Moist Mixed Grassland | Needle-and- thread[5]<br>Junegrass | Tp34 R5 W3 | Ungrazed plots protected from livestock for over 15 years.<br>Grazed plots heavily grazed for over 15 years |
| Kernen 2004 | Loamy<br>Lacustrine plain<br>Moist Mixed Grassland | Plains rough fescue[6]<br>Northern wheatgrass | Tp37 R4 W3 | Ungrazed plots protected from livestock for over 15 years.<br>Grazed plots heavily grazed for over 10 years |
| Outlook 2004 | Sandy<br>Lacustrine plain<br>Moist Mixed Grassland | Needle-and-thread<br>Junegrass | Tp29 R8 W3 | Ungrazed plots protected from livestock for about 15 years.<br>Grazed plots heavily grazed for over 10 years |
| Monet 2004 | Sandy<br>Hummocky<br>Shallow Lacustrine<br>Mixed Grassland | Northern wheatgrass<br>Needle-and-thread | Tp24 R15 W3 | Ungrazed plots protected from livestock for about 10 years.<br>Grazed plots moderately grazed for over 15 years |
| Kindersley 2004 | Loamy<br>Shallow lacustrine plain<br>Moist Mixed Grassland | Needle-and-thread<br>Northern wheatgrass | Tp29 R24 W3 | Ungrazed plots protected from livestock for over 8 years.<br>Grazed plots moderately grazed for over 15 years |
| Aberdeen 2004 | Sandy<br>Hummocky<br>Morainal<br>Moist Mixed Grassland | Needle-and-thread<br>Northern wheatgrass<br>Plains rough fescue | Tp37 R2 W3 | Lightly grazed plots are located in a remote section of the range management unit.<br>Grazed plots heavily grazed for more than 10 years. |
| Macrorie 2004 | Loamy<br>Hummocky<br>morainal<br>Moist Mixed Grassland | Northern wheatgrass | Tp26 R9 W3 | Ungrazed plots protected from livestock for over 15 years.<br>Grazed plots heavily grazed for over 10 years |

[1] *Elymus lanceolatus* [2] *Koeleria macrantha* [3] *Nassella viridula* [4] *Bouteloua gracilis*

[5] *Hesperostipa comata* [6] *Festuca hallii*

## 3.3 Results

### 3.3.1 Plant species composition as affected by grazing

Species composition was highly variable among the 9 study sites and between grazed and ungrazed areas within sites (Appendix 3.2). Notable differences between grazed and ungrazed areas occur for litter and ubiquitous indicator species such as fringed sage (*Artemisia frigida*) and clubmoss (*Selaginella densa*). Litter cover ranged from 22 to 86% in ungrazed areas while litter cover in grazed grasslands ranged from 0 to 32% among the 9 study sites. Cover of fringed sage, an indicator of prolonged heavy grazing, ranged from 1 to 8% in ungrazed sites and from 2 to 28 % in grazed grasslands. Dense clubmoss, another indicator of prolonged heavy grazing, ranged from 0 to 12% on ungrazed grasslands and from 5 to 80% in grazed areas. These differences indicate that plant community composition is different in grazed and ungrazed areas.

### 3.3.2 Soil organic carbon as affected by grazing, soil texture and soil depth

Soil organic carbon was not significantly affected by grazing at any depth increment or for the whole profile ($P > 0.1$) (Table 3.2), even though on average, grazed grasslands had 24% more SOC than the control (Table 3.3). The effect of soil texture on SOC was significant at depth increments between 10-50 cm and for the whole profile, with loamy soils having greater SOC than sandy soils which is consistent with results from Chapter 2. Interactions between grazing treatments and soil texture were not significant for SOC at any depths.

### 3.3.3 Soil bulk density as affected by grazing, soil texture and soil depth

Soil bulk density was 0.09 g cm$^{-3}$ greater ($P<0.1$) in grazed than ungrazed sites and 0.18 g cm$^{-3}$ greater in sandy than loamy sites (Table 3.4). Mean bulk density generally increased with increasing soil depth and that in the top 3 cm was significantly lower than all other depths (Table 3.5).

**Table 3.2.** Means comparisons for the effects of soil texture and grazing on soil organic carbon (SOC) in the Prairie Ecozone of Saskatchewan.

| Comparison | | | -------0-3 cm ------- | | | ------3-10 cm------ | | | ---10-20 cm--- | | | ----20-30 cm---- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | (mg cm$^{-3}$) | | | | | | | | | | | |
| U (ungrazed) | vs. | G (grazed) | 2.58 | 7.65 | 0.74 | 5.73 | 4.91 | 0.26 | 3.68 | 2.97 | 0.23 | 1.52 | 1.98 | 0.45 |
| S (sand) | vs. | L (loam) | 3.04 | 7.68 | 0.70 | -6.55 | 4.88 | 0.20 | -7.56 | 2.50 | **0.01** | -5.78 | 1.42 | **0.00** |
| G x S | vs. | G x L | 7.47 | 12.10 | 0.92 | -1.87 | 7.45 | 0.99 | -5.62 | 3.86 | 0.49 | -5.88 | 2.27 | **0.09** |
| U x L | vs. | G x L | 7.33 | 12.49 | 0.93 | 8.42 | 7.69 | 0.70 | 3.67 | 3.99 | 0.79 | 0.08 | 2.34 | 1.00 |
| U x S | vs. | G x S | 0.38 | 11.04 | 1.00 | 1.44 | 6.80 | 1.00 | 0.88 | 3.52 | 0.99 | 0.38 | 2.07 | 1.00 |
| U x S | vs. | U x L | 0.52 | 11.48 | 1.00 | -8.85 | 7.07 | 0.61 | -8.40 | 3.66 | 0.15 | -5.58 | 2.15 | **0.09** |

[1] Difference in means between factors A and B.

**Table 3.2**. Continued.

| Comparison | | | 30-40 cm | | | 40-50 cm | | | 0-50 cm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | $(mg\ cm^{-3})$ | | | | | | $(kg\ m^{-2})$ | | |
| U (ungrazed) | vs. | G (grazed) | 1.66 | 1.47 | 0.28 | 1.60 | 1.25 | 0.22 | 1.32 | 1.17 | 0.27 |
| S (sand) | vs. | L (loam) | -4.51 | 1.04 | **0.00** | -4.06 | 0.84 | **0.00** | -2.55 | 1.04 | **0.03** |
| G x S | vs. | G x L | -5.10 | 1.61 | **0.03** | -4.60 | 1.28 | **0.01** | -2.02 | 1.62 | 0.61 |
| U x L | vs. | G x L | -0.11 | 1.67 | 1.00 | -0.02 | 1.32 | 1.00 | 1.17 | 1.68 | 0.90 |
| U x S | vs. | G x S | 1.31 | 1.47 | 0.81 | 1.33 | 1.17 | 0.68 | 0.50 | 1.48 | 0.99 |
| U x S | vs. | U x L | -3.69 | 1.53 | 0.12 | -3.26 | 1.22 | **0.08** | -2.69 | 1.54 | 0.34 |

**Table 3.3.** Means for soil organic carbon (SOC) in grazed and ungrazed sites in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 6 grazed and 6 ungrazed plots.

| | | | soil depth (cm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Texture | Site | Treatment | 0-50 | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | SOC (kg m$^{-2}$) | SOC (mg cm$^{-3}$) | | | | | |
| Sandy | Biddulph | Ungrazed | 4.2 | 24.7 | 12.0 | 7.7 | 7.5 | 6.5 | 5.0 |
| | | Grazed | 3.1 | 12.9 | 9.3 | 6.9 | 5.9 | 4.3 | 4.0 |
| | Monet | Ungrazed | 5.1 | 30.9 | 19.0 | 10.1 | 6.7 | 6.4 | 5.2 |
| | | Grazed | 6.6 | 54.1 | 27.6 | 11.4 | 8.4 | 6.0 | 4.6 |
| | Outlook | Ungrazed | 3.4 | 20.4 | 7.4 | 5.4 | 5.4 | 5.9 | 5.7 |
| | | Grazed | 1.8 | 8.8 | 6.3 | 4.0 | 2.8 | 2.5 | 2.1 |
| | Kindersley | Ungrazed | 5.7 | 18.8 | 16.6 | 13.9 | 9.9 | 8.4 | 7.9 |
| | | Grazed | 5.7 | 25.1 | 15.6 | 10.0 | 10.0 | 9.8 | 8.6 |
| | Aberdeen | Ungrazed | 8.7 | 60.7 | 37.5 | 18.0 | 10.0 | 7.9 | 7.0 |
| | | Grazed | 7.5 | 53.7 | 27.6 | 15.9 | 10.7 | 7.4 | 6.0 |
| | **Means** | **Ungrazed** | **5.4** | **31.1** | **18.5** | **11.0** | **7.9** | **7.0** | **6.2** |
| | | **Grazed** | **4.9** | **30.9** | **17.3** | **9.6** | **7.6** | **6.0** | **5.1** |
| Loamy | Matador North | Ungrazed | 6.5 | 21.6 | 18.5 | 14.3 | 11.7 | 10.4 | 9.6 |
| | | Grazed | 6.7 | 23.9 | 17.0 | 15.5 | 13.3 | 10.3 | 9.2 |
| | Matador South | Ungrazed | 7.7 | 26.8 | 24.1 | 17.2 | 14.3 | 10.5 | 10.1 |
| | | Grazed | 8.2 | 30.0 | 25.6 | 19.6 | 15.4 | 11.3 | 9.2 |
| | Kernen | Ungrazed | 12.8 | 58.6 | 44.0 | 31.0 | 20.2 | 16.1 | 12.5 |
| | | Grazed | 4.4 | 30.2 | 14.2 | 9.4 | 6.6 | 4.9 | 3.8 |
| | Macrorie | Ungrazed | 7.5 | 42.5 | 35.9 | 17.1 | 8.8 | 6.4 | 4.8 |
| | | Grazed | 5.7 | 43.1 | 20.2 | 8.9 | 7.7 | 7.1 | 5.9 |
| | **Means** | **Ungrazed** | **8.6** | **37.4** | **30.6** | **19.9** | **13.8** | **10.9** | **9.3** |
| | | **Grazed** | **6.3** | **31.8** | **19.3** | **13.4** | **10.8** | **8.4** | **7.0** |

**Table 3.4.** Means comparisons for bulk density in grazed and ungrazed grasslands, loamy and sandy soils, and throughout the soil profile for 9 sites located in the Prairie Ecozone of Saskatchewan.

| | Comparison | | Difference | | |
|---|---|---|---|---|---|
| Parameter | Factor A | Factor B | A-B (g cm$^{-3}$) | SE | P |
| Grazing treatment | Ungrazed | Grazed | -0.09 | 0.05 | **0.06** |
| Soil texture | Sandy | Loamy | 0.18 | 0.05 | **0.00** |
| Soil depth (cm) | 3-10 | 0-3 | 0.25 | 0.07 | **0.01** |
| | 10-20 | 0-3 | 0.33 | 0.07 | **0.00** |
| | 20-30 | 0-3 | 0.39 | 0.07 | **0.00** |
| | 30-40 | 0-3 | 0.41 | 0.07 | **0.00** |
| | 40-50 | 0-3 | 0.47 | 0.07 | **0.00** |
| | 10-20 | 3-10 | 0.08 | 0.07 | 0.87 |
| | 20-30 | 3-10 | 0.14 | 0.07 | 0.38 |
| | 30-40 | 3-10 | 0.16 | 0.07 | 0.26 |
| | 40-50 | 3-10 | 0.22 | 0.07 | **0.04** |
| | 20-30 | 10-20 | 0.06 | 0.07 | 0.96 |
| | 30-40 | 10-20 | 0.08 | 0.07 | 0.90 |
| | 40-50 | 10-20 | 0.14 | 0.07 | 0.42 |
| | 30-40 | 20-30 | 0.02 | 0.07 | 1.00 |
| | 40-50 | 20-30 | 0.08 | 0.07 | 0.89 |
| | 40-50 | 30-40 | 0.06 | 0.07 | 0.96 |

**Table 3.5.** Soil bulk density throughout the soil profile in grazed and ungrazed grassland in the Prairie Ecozone of Saskatchewan.

| | | | Soil depth (cm) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Texture class | Site name | Treatment | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | Bulk density (mg $cm^{-3}$) | | | | | |
| Loamy | Matador North | Ungrazed | 0.49 | 0.86 | 0.99 | 1.12 | 1.14 | 1.18 |
| | | Grazed | 0.72 | 1.07 | 1.08 | 1.15 | 1.17 | 1.25 |
| | Matador South | Ungrazed | 0.43 | 0.88 | 0.96 | 1.18 | 1.18 | 1.26 |
| | | Grazed | 0.51 | 0.94 | 1.09 | 1.15 | 1.21 | 1.27 |
| | Kernen | Ungrazed | 0.99 | 1.08 | 1.22 | 1.34 | 1.40 | 1.45 |
| | | Grazed | 1.33 | 1.52 | 1.50 | 1.43 | 1.42 | 1.45 |
| | Macrorie | Ungrazed | 1.08 | 1.27 | 1.29 | 1.31 | 1.38 | 1.55 |
| | | Grazed | 1.38 | 1.51 | 1.54 | 1.58 | 1.50 | 1.53 |
| | **Means** | **Ungrazed** | **0.74** | **1.03** | **1.12** | **1.23** | **1.27** | **1.34** |
| | | **Grazed** | **0.99** | **1.26** | **1.30** | **1.33** | **1.33** | **1.38** |
| Sandy | Biddulph | Ungrazed | 0.75 | 1.32 | 1.49 | 1.59 | 1.62 | 1.63 |
| | | Grazed | 0.70 | 1.37 | 1.48 | 1.63 | 1.66 | 1.75 |
| | Monet | Ungrazed | 1.04 | 1.24 | 1.37 | 1.40 | 1.42 | 1.48 |
| | | Grazed | 1.00 | 1.30 | 1.42 | 1.44 | 1.42 | 1.43 |
| | Outlook | Ungrazed | 1.31 | 1.44 | 1.46 | 1.47 | 1.48 | 1.54 |
| | | Grazed | 1.65 | 1.58 | 1.62 | 1.67 | 1.70 | 1.75 |
| | Kindersley | Ungrazed | 1.06 | 1.20 | 1.25 | 1.28 | 1.29 | 1.33 |
| | | Grazed | 1.03 | 1.12 | 1.19 | 1.32 | 1.36 | 1.38 |
| | Aberdeen | Ungrazed | 1.02 | 1.23 | 1.44 | 1.42 | 1.45 | 1.58 |
| | | Grazed | 1.26 | 1.34 | 1.35 | 1.31 | 1.29 | 1.37 |
| | **Means** | **Ungrazed** | **1.04** | **1.29** | **1.40** | **1.43** | **1.45** | **1.51** |
| | | **Grazed** | **1.13** | **1.34** | **1.41** | **1.47** | **1.49** | **1.54** |

### 3.3.4 Fine root biomass as affected by grazing, soil texture and soil depth

Fine root biomass was not significantly affected by grazing at any depth increments or the whole soil profile ($P > 0.1$) (Table 3.6), even though for loamy sites, it was 30% higher in the grazed than the ungrazed sites on average (Table 3.7). Loamy soils had significantly higher fine root biomass at depth increments between 3-40 cm. Interactions between grazing treatment and soil texture were not significant for fine root biomass at any depths.

**Table 3.6.** Means comparisons for the effects of soil texture and grazing on fine root biomass in the Prairie Ecozone of Saskatchewan.

| Comparison | | | ------0-3 cm ------ | | | ---3-10 cm--- | | | ---10-20 cm-- | | | --20-30 cm-- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ------(mg cm$^{-3}$)------ | | | | | | | | | | | |
| U (ungrazed) | vs. | G (grazed) | -0.32 | 1.22 | 0.80 | -0.60 | 0.35 | 0.11 | -0.27 | 0.22 | 0.23 | -0.08 | 0.21 | 0.71 |
| S (sand) | vs. | L (loam) | 1.85 | 1.14 | 0.12 | 1.00 | 0.30 | **0.00** | 0.49 | 0.20 | **0.02** | 0.41 | 0.19 | **0.05** |
| G x S | vs. | G x L | 2.17 | 1.81 | 0.64 | 0.84 | 1.90 | 0.27 | 0.63 | 0.30 | 0.20 | 0.41 | 0.30 | 0.55 |
| U x L | vs. | G x L | 0.41 | 1.87 | 1.00 | -0.47 | -1.02 | 0.74 | 0.02 | 0.31 | 1.00 | 0.01 | 0.31 | 1.00 |
| U x S | vs. | G x S | -0.14 | 1.66 | 1.00 | -0.34 | -0.83 | 0.84 | -0.32 | 0.27 | 0.65 | 0.02 | 0.27 | 1.00 |
| U x S | vs. | U x L | 1.61 | 1.72 | 0.78 | 0.97 | 2.31 | 0.14 | 0.29 | 0.29 | 0.75 | 0.42 | 0.28 | 0.48 |

[1] Difference in means between factors A and B.

**Table 3.6.** Continued

| Comparison | | | -----30-40 cm----- | | | --40-50 cm--- | | | ---0-50 cm-- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ------(mg cm$^{-3}$)------ | | | | | | ------(kg m$^{-2}$)------ | | |
| U (ungrazed) | vs. | G (grazed) | -0.15 | 0.15 | 0.35 | -0.01 | 0.16 | 0.93 | -0.10 | 0.11 | 0.35 |
| S (sand) | vs. | L (loam) | 0.34 | 0.13 | **0.02** | 0.25 | 0.14 | 0.10 | 0.28 | 0.09 | **0.01** |
| G x S | vs. | G x L | 0.42 | 0.21 | 0.22 | 0.22 | 0.23 | 0.76 | 0.30 | 0.14 | 0.21 |
| U x L | vs. | G x L | 0.03 | 0.21 | 1.00 | 0.00 | 0.24 | 1.00 | -0.01 | 0.15 | 1.00 |
| U x S | vs. | G x S | -0.16 | 0.19 | 0.84 | 0.08 | 0.21 | 0.98 | -0.07 | 0.13 | 0.95 |
| U x S | vs. | U x L | 0.24 | 0.20 | 0.64 | 0.30 | 0.22 | 0.54 | 0.24 | 0.13 | 0.33 |

**Table 3.7.** Means for fine root biomass (FRB) in grazed and ungrazed sites in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 6 grazed and 6 ungrazed plots.

|  |  |  | Soil depth (cm) |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| Texture | Site | Treatment | 0-50 | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
|  |  |  | FRB (kg $m^{-2}$) | FRB (mg $cm^{-3}$) |  |  |  |  |  |
| Loamy | Matador North | Ungrazed | 0.6 | 8.8 | 1.7 | 0.8 | 0.6 | 0.5 | 0.3 |
|  |  | Grazed | 0.5 | 6.2 | 1.8 | 0.8 | 0.6 | 0.5 | 0.3 |
|  | Matador South | Ungrazed | 0.7 | 9.8 | 1.9 | 0.8 | 0.7 | 0.8 | 0.6 |
|  |  | Grazed | 0.8 | 10.8 | 2.7 | 1.1 | 0.9 | 0.7 | 0.5 |
|  | Kernen | Ungrazed | 0.6 | 8.6 | 1.7 | 1.0 | 0.6 | 0.5 | 0.4 |
|  |  | Grazed | 1.2 | 12.0 | 3.4 | 2.1 | 1.7 | 1.5 | 1.1 |
|  | Macrorie | Ungrazed | 0.8 | 7.4 | 1.8 | 1.3 | 1.2 | 0.9 | 0.7 |
|  |  | Grazed | 1.0 | 10.0 | 2.9 | 1.3 | 1.1 | 1.2 | 1.0 |
|  | **Means** | **Ungrazed** | **0.7** | **8.6** | **1.8** | **1.0** | **0.8** | **0.7** | **0.5** |
|  |  | **Grazed** | **0.9** | **9.7** | **2.7** | **1.3** | **1.1** | **1.0** | **0.7** |
| Sandy | Biddulph | Ungrazed | 0.7 | 12.9 | 1.8 | 0.6 | 0.4 | 0.4 | 0.3 |
|  |  | Grazed | 0.6 | 6.8 | 1.9 | 0.8 | 0.4 | 0.8 | 0.2 |
|  | Monet | Ungrazed | 1.1 | 9.3 | 3.8 | 1.9 | 1.6 | 1.3 | 1.1 |
|  |  | Grazed | 1.3 | 12.2 | 4.1 | 2.1 | 1.7 | 1.3 | 1.0 |
|  | Outlook | Ungrazed | 0.8 | 5.3 | 2.3 | 1.2 | 1.3 | 1.1 | 1.3 |
|  |  | Grazed | 0.8 | 6.3 | 3.3 | 1.7 | 0.8 | 0.7 | 0.6 |
|  | Kindersley | Ungrazed | 0.6 | 5.4 | 1.9 | 1.1 | 0.7 | 0.8 | 0.8 |
|  |  | Grazed | 0.7 | 5.8 | 2.3 | 1.1 | 0.9 | 0.8 | 0.8 |
|  | Aberdeen | Ungrazed | 1.0 | 11.0 | 3.2 | 1.6 | 1.5 | 1.0 | 0.7 |
|  |  | Grazed | 1.1 | 11.3 | 3.0 | 1.9 | 1.4 | 1.1 | 0.9 |
|  | **Means** | **Ungrazed** | **0.9** | **8.8** | **2.6** | **1.3** | **1.1** | **0.9** | **0.8** |
|  |  | **Grazed** | **0.9** | **8.5** | **2.9** | **1.5** | **1.0** | **0.9** | **0.7** |

### 3.3.5 Medium root biomass as affected by grazing, soil texture and soil depth

Medium root biomass was not significantly different between grazed and ungrazed plots at any depth increments or for the whole soil profile ($P > 0.1$) (Table 3.8). More than 2/3 of the medium root biomass was in the top 10 cm of the soil (Table 3.9). Soil texture did not significantly affect medium root biomass, except 30-40 cm depth where loamy soils had greater medium root biomass than sandy soils. None of the interactions between grazing and soil treatments for medium roots was significant.

**Table 3.8.** Means comparisons for the effects of soil texture and grazing on medium root biomass in the Prairie Ecozone of Saskatchewan.

| Comparison | | | ----0-3 cm ---- | | | 3-10 cm | | | 10-20 cm | | | 20-30 cm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ---------------------------------------(mg cm$^{-3}$)--------------------------------------- | | | | | | | | | | | |
| U (ungrazed) | vs. | G (grazed) | -0.75 | 1.81 | 0.69 | -0.12 | 0.37 | 0.74 | -0.04 | 0.13 | 0.77 | 0.08 | 0.08 | 0.31 |
| S (sand) | vs. | L (loam) | 1.17 | 1.81 | 0.53 | -0.28 | 0.37 | 0.46 | -0.08 | 0.13 | 0.56 | -0.09 | 0.08 | 0.28 |
| G x S | vs. | G x L | -0.63 | 2.80 | 1.00 | -0.58 | 0.57 | 0.75 | -0.17 | 0.20 | 0.83 | -0.18 | 0.11 | 0.42 |
| U x L | vs. | G x L | -2.31 | 2.90 | 0.86 | -0.47 | 0.59 | 0.86 | -0.14 | 0.21 | 0.90 | -0.05 | 0.12 | 0.97 |
| U x S | vs. | G x S | 0.89 | 2.56 | 0.98 | 0.02 | 0.52 | 1.00 | 0.01 | 0.18 | 1.00 | 0.16 | 0.10 | 0.46 |
| U x S | vs. | U x L | 2.57 | 2.66 | 0.77 | -0.09 | 0.55 | 1.00 | -0.02 | 0.19 | 1.00 | 0.03 | 0.11 | 1.00 |

[1] Difference in means between factors A and B.

**Table 3.8.** Continued.

| Comparison | | | --30-40 cm --- | | | 40-50 cm | | | 0-50 cm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | --------------------(mg cm$^{-3}$)-------------------- | | | | | | ----(kg m$^{-2}$)---- | | |
| U (ungrazed) | vs. | G (grazed) | 0.07 | 0.08 | 0.37 | 0.07 | 0.07 | 0.35 | -0.01 | 0.09 | 0.89 |
| S (sand) | vs. | L (loam) | -0.15 | 0.07 | **0.05** | -0.16 | 0.07 | 0.03 | -0.03 | 0.09 | 0.73 |
| G x S | vs. | G x L | -0.23 | 0.10 | 0.17 | -0.25 | 0.10 | 0.08 | -0.15 | 0.14 | 0.74 |
| U x L | vs. | G x L | -0.06 | 0.11 | 0.96 | -0.07 | 0.10 | 0.88 | -0.14 | 0.15 | 0.79 |
| U x S | vs. | G x S | 0.11 | 0.10 | 0.64 | 0.12 | 0.09 | 0.51 | 0.07 | 0.13 | 0.95 |
| U x S | vs. | U x L | -0.06 | 0.10 | 0.93 | -0.05 | 0.09 | 0.93 | 0.06 | 0.14 | 0.97 |

**Table 3.9.** Means for medium root biomass (MRB) in grazed and ungrazed sites in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 6 grazed and 6 ungrazed plots.

| | | | Soil depth (cm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Texture | Site | Treatment | 0-50 | 0-3 | 3-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| | | | MRB (kg m$^{-2}$) | MRB (mg cm$^{-3}$) | | | | | |
| Loamy | Matador North | Ungrazed | 0.9 | 14.0 | 3.4 | 1.1 | 0.6 | 0.4 | 0.4 |
| | | Grazed | 0.7 | 10.1 | 3.1 | 0.9 | 0.6 | 0.4 | 0.2 |
| | Matador South | Ungrazed | 0.6 | 5.5 | 1.9 | 0.9 | 0.7 | 0.7 | 0.6 |
| | | Grazed | 0.9 | 13.7 | 2.5 | 1.1 | 0.6 | 0.5 | 0.4 |
| | Kernen | Ungrazed | 0.4 | 5.1 | 1.5 | 0.5 | 0.3 | 0.1 | 0.1 |
| | | Grazed | 0.4 | 6.1 | 1.1 | 0.6 | 0.3 | 0.2 | 0.1 |
| | Macrorie | Ungrazed | 0.4 | 6.0 | 1.2 | 0.6 | 0.3 | 0.2 | 0.2 |
| | | Grazed | 0.6 | 10.6 | 1.9 | 0.8 | 0.5 | 0.3 | 0.2 |
| | **Means** | **Ungrazed** | **0.6** | **7.7** | **2.0** | **0.8** | **0.5** | **0.4** | **0.3** |
| | | **Grazed** | **0.6** | **10.1** | **2.2** | **0.9** | **0.5** | **0.3** | **0.2** |
| Sandy | Biddulph | Ungrazed | 0.5 | 7.2 | 1.5 | 0.6 | 0.3 | 0.2 | 0.2 |
| | | Grazed | 0.6 | 12.5 | 2.1 | 0.5 | 0.2 | 0.1 | 0.0 |
| | Monet | Ungrazed | 0.5 | 9.1 | 1.1 | 0.6 | 0.4 | 0.3 | 0.2 |
| | | Grazed | 0.7 | 14.4 | 1.5 | 0.8 | 0.4 | 0.3 | 0.2 |
| | Outlook | Ungrazed | 0.8 | 12.3 | 2.7 | 1.1 | 0.7 | 0.4 | 0.4 |
| | | Grazed | 0.5 | 4.4 | 2.6 | 1.3 | 0.4 | 0.3 | 0.2 |
| | Kindersley | Ungrazed | 0.4 | 4.3 | 1.0 | 0.6 | 0.4 | 0.3 | 0.2 |
| | | Grazed | 0.4 | 4.1 | 1.2 | 0.7 | 0.3 | 0.4 | 0.5 |
| | Aberdeen | Ungrazed | 0.6 | 9.7 | 1.5 | 0.7 | 0.5 | 0.3 | 0.2 |
| | | Grazed | 0.3 | 4.1 | 0.8 | 0.4 | 0.2 | 0.1 | 0.0 |
| | **Means** | **Ungrazed** | **0.5** | **8.5** | **1.6** | **0.7** | **0.4** | **0.3** | **0.2** |
| | | **Grazed** | **0.5** | **7.9** | **1.7** | **0.7** | **0.3** | **0.2** | **0.2** |

### 3.3.6 Aboveground biomass as affected by grazing, soil texture and soil depth

Grazing had a significant affect on herbaceous, litter, and total aboveground biomass. Herbaceous biomass was 130 g m$^{-2}$ greater in ungrazed than grazed grassland (Tables 3.10, 3.11). Litter biomass was 205.8 g m$^{-2}$ greater and total biomass was 330 g m$^{-2}$ greater on ungrazed grasslands relative to grazed grasslands, respectively. Herbaceous, litter, and total biomass was not significantly affected by soil texture. Interactions between grazing treatments and soil were not significant for herbaceous, litter, and total biomass.

**Table 3.10.** Means comparisons for the effects of soil texture and grazing on herbaceous, litter, shrub, and total biomass in the Prairie Ecozone of Saskatchewan.

| Comparison | | | Herbaceous biomass | | | ---- Litter biomass ---- | | | --- Total biomass --- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor A | | Factor B | A-B[1] | S.E. | P | A-B | S.E. | P | A-B | S.E. | P |
| | | | ---------------------------------------(g $cm^{-2}$)--------------------------------- | | | | | | | | |
| U (ungrazed) | vs. | G (grazed) | 130.20 | 32.72 | **0.00** | 205.80 | 40.89 | **0.00** | 330.70 | 53.16 | **0.00** |
| S (sand) | vs. | L (loam) | -26.78 | 45.96 | 0.57 | -105.30 | 60.66 | 0.10 | -136.70 | 92.81 | 0.16 |
| G x S | vs. | G x L | -1.17 | 52.44 | 1.00 | -48.33 | 60.76 | 0.86 | -49.50 | 81.14 | 0.93 |
| U x L | vs. | G x L | 126.73 | 54.16 | 0.14 | 206.67 | 62.75 | **0.02** | 333.20 | 83.80 | **0.01** |
| U x S | vs. | G x S | 134.00 | 47.88 | **0.06** | 180.50 | 55.46 | **0.03** | 302.70 | 74.07 | **0.01** |
| U x S | vs. | U x L | 6.10 | 49.75 | 1.00 | -74.50 | 57.64 | 0.58 | -79.95 | 76.98 | 0.73 |

[1] Difference in means between factors A and B.

**Table 3.11.** Means for herbaceous, litter, and total aboveground biomass in grazed and ungrazed sites in the Prairie Ecozone of Saskatchewan. Values are means of 3 subsamples from 6 grazed and 6 ungrazed plots.

| Texture | Site | Treatment | Herbaceous | Litter | Total aboveground |
|---|---|---|---|---|---|
| | | | | ---Biomass (g m$^{-2}$)--- | |
| Loamy | Matador | Ungrazed | 208 | 251 | 459 |
| | North | Grazed | 108 | 171 | 279 |
| | Matador | Ungrazed | 163 | 335 | 497 |
| | South | Grazed | 94 | 4 | 98 |
| | Kernen | Ungrazed | 373 | 225 | 598 |
| | | Grazed | 157 | 0 | 157 |
| | Macroric | Ungrazed | 262 | 456 | 718 |
| | | Grazed | 122 | 137 | 259 |
| | **Means** | **Ungrazed** | **252** | **317** | **568** |
| | | **Grazed** | **120** | **78** | **198** |
| Sandy | Biddulph | Ungrazed | 187 | 336 | 524 |
| | | Grazed | 37 | 18 | 55 |
| | Monet | Ungrazed | 235 | 188 | 422 |
| | | Grazed | 83 | 21 | 104 |
| | Outlook | Ungrazed | 162 | 142 | 257 |
| | | Grazed | 76 | 0 | 76 |
| | Kindersley | Ungrazed | 186 | 158 | 344 |
| | | Grazed | 133 | 60 | 193 |
| | Aberdeen | Ungrazed | 394 | 176 | 570 |
| | | Grazed | 188 | 4 | 192 |
| | **Means** | **Ungrazed** | **233** | **200** | **423** |
| | | **Grazed** | **103** | **21** | **124** |

## 3.4 Discussion

Large roots were absent from the study sites because shrub occurrence was seldom within the plots. Root biomass and SOC were not significantly affected by grazing, even though OSC tended to be 24% higher in the control than the grazed plots. Reduced SOC by heavy grazing has been reported in Fescue grasslands of Alberta (Dormaar et al. 1989) and many other grasslands (Bauer et al. 1987, Conant et al. 2001). They speculated that the greater SOC in ungrazed grasslands could be caused by the cumulative effects of C removal from the animals digestion process and by C removal from the system when livestock are exported from grazing areas. Abril and Bucher (2001) conducted studies in semi-arid savannas and woodlands in Argentina and estimated 58 Mg C ha$^{-1}$, or 78% of the pre grazing total, was removed from the system since the introduction of cattle into the area. They concluded that overgrazing by livestock affects SOC by reducing input from litter, increased decomposition due to increased temperature in denuded areas, and by altering water cycles at a site.

It is not surprising that litter and herbaceous biomass was higher in the control than the grazed plots as reported before (Henderson et al. 2004). Plant species composition was affected by grazing despite the lack of significant differences in SOC, similar to studies from Wyoming (Manley et al. 1995, Schuman et al. 1999) and Alberta (Henderson et al. 2004). Milchunas and Lauenroth (1993) conducted a worldwide review of 236 sites to assess factors related to the effects of grazing on ecosystem functions including the soil carbon balance. They concluded that soil organic matter or SOC were nearly equally divided between positive and negative response to grazing. Thus it appears that factors, other than livestock grazing have significant control on SOC content in prairie ecosystems.

Based on the results of the present study, it appears that SOC is controlled more by soil texture than grazing as reported by Henderson et al. (2004) and Potter et al. (2001). Soil texture also affected medium root biomass. Generally, the effect of soil texture on SOC and root biomass was similar to that reported in the previous chapter. Soil organic carbon was the major carbon pool in grasslands, greater than roots and aboveground biomass combined.

## Summary and Management Implications

Physical environment characteristics, plant community characteristics and GHGs were all influenced by landscape element and mowing. Landscape element and mowing contributed to differences in physical environment characteristics, plant community characteristics and GHG flux. Differences in PDIR among landscape elements, accumulated snow water equivalent and soil temperature suggest that patterns in plant community characteristics may be similar to patterns in GHG flux rates. The current study shows, however, that differences in physical environment characteristics such as soil N, WFPS and GHG flux rates were not consistent through time. Mowing modified plant community characteristics, especially species evenness, which in turn led to major increases in $CO_2$ flux and smaller increases in $CH_4$ consumption and $N_2O$ production. Soil water and soil temperature were also correlated with GHG flux, but changes in all of these factors over time make interpretation of results difficult. Along the gradient from grassland to shrub communities, soil organic carbon (SOC) had less than 5% increase, which was not significant. Large root biomass but not medium or small root biomass was higher in the shrub community than the others. Grazing did not significantly affect SOC and root biomass, even though it SOC tended to be lower at the grazed sites than the ungrazed. For all 18 sites studied, SOC was the most important carbon pool and was higher than the combination of above- and below ground biomass. Soil carbon was controlled more by soil texture than by shrub cover or grazing with loamy soils having greater SOC fluxes from native grasslands are relative small. Changes in vegetation from grassland to shrubland increased above-ground biomass but not SOC and grazing did not significantly alter soil carbon.

Canadian agriculture contributes 8.3% of Canada's total GHG emissions (Olsen et al., 2003). The Canadian government plans to mitigate agricultural GHGs by identifying best management practices that change the production and consumption of GHGs to positively influence climate change (Agriculture and Agri-Food Canada, 2003). The starting point for proposed best management practices for the Mixedgrass Prairie of Saskatchewan is to recognize the relative source and sink that rangelands represent compared to arable lands. The net emissions of GHGs from Saskatchewan rangeland are relatively low (de Jong, 1981; Corre et al., 1999) but the potential for increased emissions from rangeland is high if improperly managed (Mosier et al., 1998a; Mosier et al., 1998b). Management that leads to cover change on the prairies is an important contributor to climate change (Skinner and Majorowicz, 1999). A policy of promoting the prevention of the conversion of the Mixedgrass Prairie to arable agriculture and encouraging the conversion of croplands to perennial grasses would benefit Canadian attempts to mitigate GHGs by retaining important $CO_2$ storage, $CH_4$ sinks as well as not adding to $N_2O$ production. Rangelands may play an increasingly important role in light of increased $CO_2$ concentration and N deposition, both of which could increase productivity and increase the sink ability of Saskatchewan rangelands.

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**Appendix 1.** Soil texture along the gradient from grassland to shrub communities in the Prairie Ecozone of Saskatchewan.

| Site | Plot location | % sand | % silt | % clay | Texture class |
|---|---|---|---|---|---|
| Biddulph | Shrub 1 | 87 | 10 | 3 | S |
| Biddulph | Shrub 2 | 87 | 10 | 3 | S |
| Biddulph | Shrub 3 | 80 | 17 | 3 | LS |
| Biddulph | Ecotone | 84 | 13 | 3 | LS |
| Biddulph | Grassland 1 | 78 | 19 | 3 | LS |
| Biddulph | Grassland 2 | 81 | 16 | 3 | LS |
| | | | | | |
| Kernen | Shrub 1 | 36 | 58 | 6 | SiL |
| Kernen | Shrub 2 | 34 | 60 | 6 | SiL |
| Kernen | Shrub 3 | 40 | 52 | 8 | SiL |
| Kernen | Ecotone | 40 | 56 | 4 | SiL |
| Kernen | Grassland 1 | 34 | 60 | 6 | SiL |
| Kernen | Grassland 2 | 38 | 56 | 6 | SiL |
| | | | | | |
| Abott | Shrub 1 | 54 | 42 | 4 | SL |
| Abott | Shrub 2 | 48 | 50 | 2 | SL |
| Abbott | Shrub 3 | 50 | 48 | 2 | SL |
| Abott | Ecotone | 54 | 44 | 2 | SL |
| Abott | Grassland 1 | 68 | 30 | 2 | SL |
| Abott | Grassland 2 | 58 | 38 | 4 | SL |
| | | | | | |
| Rudy | Shrub 1 | 72 | 24 | 4 | LS |
| Rudy | Shrub 2 | 69 | 24 | 7 | SL |
| Rudy | Shrub 3 | 70 | 25 | 5 | SL |
| Rudy | Ecotone | 70 | 27 | 3 | SL |
| Rudy | Grassland 1 | 74 | 22 | 4 | LS |
| Rudy | Grassland 2 | 74 | 23 | 3 | LS |
| | | | | | |
| Mont N | Shrub 1 | 94 | 5 | 1 | S |
| Mont N | Shrub 2 | 89 | 10 | 1 | S |
| Mont N | Shrub 3 | 90 | 9 | 1 | S |
| Mont N | Ecotone | 93 | 6 | 1 | S |
| Mont N | Grassland 1 | 91 | 8 | 1 | S |
| Mont N | Grassland 2 | 90 | 9 | 1 | S |
| | | | | | |
| Mont S | Shrub 1 | 89 | 9 | 2 | S |
| Mont S | Shrub 2 | 90 | 8 | 2 | S |
| Mont S | Shrub 3 | 90 | 8 | 2 | S |
| Mont S | Ecotone | 90 | 8 | 2 | S |
| Mont S | Grassland 1 | 89 | 9 | 2 | S |
| Mont S | Grassland 2 | 90 | 8 | 2 | S |

**Appendix 1.** Continued.

| Site | Plot location | % sand | % silt | % clay | Texture class |
|---|---|---|---|---|---|
| Wilner | Shrub 2 | 54 | 40 | 6 | SL |
| Wilner | Shrub 2 | 54 | 40 | 6 | SL |
| Wilner | Shrub 3 | 56 | 38 | 6 | SL |
| Wilner | Ecotone | 50 | 48 | 2 | SL |
| Wilner | Grassland 1 | 52 | 44 | 4 | SL |
| Wilner | Grassland 2 | 50 | 46 | 4 | SL |
| Coop | Shrub 1 | 75 | 22 | 3 | LS |
| Coop | Shrub 2 | 73 | 22 | 5 | SL |
| Coop | Shrub 3 | 74 | 21 | 5 | LS |
| Coop | Ecotone | 80 | 18 | 2 | LS |
| Coop | Grassland 1 | 74 | 23 | 3 | LS |
| Coop | Grassland 2 | 82 | 15 | 3 | LS |
| Matador | Shrub 1 | 32 | 22 | 46 | C |
| Matador | Shrub 2 | 32 | 24 | 44 | C |
| Matador | Shrub 3 | 28 | 24 | 48 | C |
| Matador | Ecotone | 28 | 24 | 48 | C |
| Matador | Grassland 1 | 28 | 26 | 46 | C |
| Matador | Grassland 2 | 26 | 26 | 48 | C |

**Appendix 2.** Mean percent species and ground cover in shrub, ecotone, and grassland communities at 9 shrub sites in the Prairie Ecozone in July 2003. Values are means of 8 quadrats per plot with 3, 1, and 2 plots located in the shrub, ecotone, and grassland communities respectively.

| Sward component | Biddulph | | | Kernen | | |
|---|---|---|---|---|---|---|
| | Shrub | Ecotone | Grassland | Shrub | Ecotone | Grassland |
| | Cover (%) | | | | | |
| Snowberry canopy | 50 | 20 | 0 | 43 | 10 | 0 |
| Herbaceous litter | 28 | 25 | 23 | 17 | 50 | 43 |
| Bare ground | 2 | 0 | 0 | 0 | 0 | 0 |
| Shrub litter | 37 | 5 | 0 | 27 | 5 | 0 |
| ACH MIL | 0 | 0 | 0 | 0 | 0 | 1 |
| AGR DAS | 0 | 0 | 0 | 0 | 0 | 1 |
| AGR SMI | 2 | 0 | 1 | 0 | 0 | 1 |
| AGR SUB | 0 | 0 | 0 | 0 | 1 | 1 |
| AND SEP | 0 | 0 | 0 | 0 | 0 | 0 |
| ANE PAT | 1 | 0 | 1 | 0 | 0 | 0 |
| Arabis sp. | 0 | 0 | 0 | 0 | 0 | 0 |
| ART FRI | 0 | 3 | 0 | 0 | 0 | 2 |
| ART LUD | 0 | 0 | 0 | 1 | 1 | 0 |
| BOU GRA | 0 | 0 | 1 | 0 | 0 | 0 |
| CAL LON | 3 | 0 | 0 | 0 | 0 | 0 |
| Carex spp. | 10 | 41 | 28 | 1 | 3 | 1 |
| CER ARV | 0 | 0 | 0 | 0 | 0 | 0 |
| ELE COM | 0 | 0 | 0 | 0 | 0 | 0 |
| EQU HYE | 0 | 0 | 0 | 0 | 0 | 0 |
| ERY ASP | 0 | 0 | 0 | 0 | 0 | 0 |
| FES ALT | 0 | 0 | 0 | 26 | 5 | 34 |
| FRA VIR | 0 | 0 | 0 | 0 | 0 | 0 |
| GAL BOR | 0 | 0 | 0 | 0 | 1 | 1 |
| GAU COC | 0 | 1 | 0 | 0 | 0 | 0 |
| GLY LEP | 0 | 0 | 0 | 0 | 0 | 0 |
| HEL HOO | 1 | 0 | 0 | 0 | 0 | 1 |
| HET VIL | 0 | 0 | 0 | 0 | 0 | 0 |
| JUN BAL | 0 | 0 | 0 | 0 | 0 | 0 |
| KOE MAC | 0 | 0 | 0 | 0 | 0 | 0 |
| KRA LAN | 0 | 0 | 0 | 0 | 0 | 0 |
| PHL HOO | 0 | 0 | 0 | 0 | 0 | 0 |
| POA PRA | 6 | 0 | 0 | 0 | 15 | 11 |
| ROS WOO | 2 | 0 | 5 | 0 | 0 | 0 |
| SEL DEN | 0 | 2 | 0 | 0 | 0 | 0 |
| SPO CRY | 0 | 0 | 0 | 0 | 0 | 0 |
| STI COM | 0 | 19 | 38 | 0 | 0 | 0 |
| STI CUR | 0 | 0 | 0 | 3 | 14 | 3 |
| STI VIR | 0 | 0 | 0 | 0 | 0 | 0 |
| SYM OCC | 7 | 5 | 0 | 9 | 5 | 0 |
| VIC AME | 0 | 0 | 0 | 0 | 0 | 0 |

**Appendix 2.** Continued

| | -------------------Abbott------------------ | | | -------------------Rudy-------------------- | | |
|---|---|---|---|---|---|---|
| Sward component | Shrub | Ecotone | Grassland | Shrub | Ecotone | Grassland |
| | ------------------------------Cover (%)------------------------------ | | | | | |
| Snowberry canopy | 58 | 25 | 0 | 52 | 15 | 0 |
| Herbaceous litter | 25 | 50 | 43 | 13 | 15 | 10 |
| Bare ground | 2 | 0 | 0 | 0 | 0 | 0 |
| Shrub litter | 12 | 0 | 0 | 23 | 0 | 0 |
| ACH MIL | 0 | 0 | 0 | 0 | 0 | 0 |
| AGR DAS | 1 | 2 | 1 | 0 | 0 | 0 |
| AGR SMI | 0 | 0 | 0 | 0 | 0 | 3 |
| AGR SUB | 1 | 0 | 0 | 0 | 0 | 0 |
| AND SEP | 0 | 0 | 0 | 0 | 0 | 1 |
| ANE PAT | 0 | 0 | 0 | 0 | 0 | 0 |
| Arabis sp. | 0 | 0 | 0 | 0 | 0 | 0 |
| ART FRI | 0 | 0 | 1 | 1 | 0 | 5 |
| ART LUD | 1 | 0 | 0 | 0 | 0 | 0 |
| BOU GRA | 0 | 0 | 0 | 0 | 21 | 34 |
| CAL LON | 0 | 0 | 0 | 0 | 0 | 0 |
| Carex spp. | 5 | 21 | 8 | 9 | 30 | 3 |
| CER ARV | 0 | 0 | 0 | 0 | 0 | 0 |
| ELE COM | 0 | 0 | 0 | 1 | 1 | 0 |
| EQU HYE | 0 | 0 | 0 | 0 | 0 | 0 |
| ERY ASP | 0 | 0 | 0 | 0 | 0 | 0 |
| FES ALT | 13 | 4 | 0 | 0 | 0 | 0 |
| FRA VIR | 0 | 0 | 0 | 0 | 0 | 0 |
| GAL BOR | 1 | 0 | 0 | 0 | 0 | 0 |
| GAU COC | 0 | 0 | 0 | 0 | 0 | 0 |
| GLY LEP | 0 | 0 | 0 | 0 | 0 | 0 |
| HEL HOO | 0 | 0 | 0 | 0 | 0 | 0 |
| HET VIL | 0 | 0 | 0 | 0 | 0 | 0 |
| JUN BAL | 0 | 0 | 0 | 1 | 0 | 0 |
| KOE MAC | 0 | 0 | 0 | 1 | 1 | 16 |
| KRA LAN | 0 | 0 | 0 | 0 | 0 | 0 |
| PHL HOO | 0 | 0 | 0 | 0 | 0 | 0 |
| POA PRA | 27 | 9 | 14 | 5 | 1 | 0 |
| ROS WOO | 1 | 0 | 0 | 3 | 0 | 0 |
| SEL DEN | 0 | 0 | 0 | 0 | 4 | 26 |
| SPO CRY | 0 | 0 | 0 | 0 | 0 | 0 |
| STI COM | 5 | 15 | 37 | 12 | 20 | 11 |
| STI CUR | 0 | 0 | 0 | 0 | 0 | 0 |
| STI VIR | 0 | 0 | 0 | 0 | 0 | 0 |
| SYM OCC | 13 | 6 | 0 | 13 | 5 | 0 |
| VIC AME | 0 | 0 | 0 | 0 | 0 | 0 |

**Appendix 2.** continued

| Sward component | ------------Montrose north | -------------- | -------------- | ------------Montrose south | ------------- | ------------- |
|---|---|---|---|---|---|---|
| | Shrub | Ecotone | Grassland | Shrub | Ecotone | Grassland |
| | ------------------------------ | ------------------------------ | ------------Cover (%) | ------------------------------ | ------------------------------ | ------------------------------ |
| Snowberry canopy | 52 | 10 | 0 | 75 | 45 | 0 |
| Herbaceous litter | 17 | 5 | 1 | 0 | 0 | 30 |
| Bare ground | 0 | 10 | 5 | 0 | 5 | 23 |
| Shrub litter | 10 | 1 | 0 | 95 | 20 | 0 |
| ACH MIL | 0 | 0 | 0 | 0 | 0 | 0 |
| AGR DAS | 0 | 0 | 0 | 0 | 0 | 0 |
| AGR SMI | 1 | 5 | 2 | 0 | 5 | 6 |
| AGR SUB | 0 | 0 | 0 | 1 | 0 | 0 |
| AND SEP | 0 | 0 | 0 | 0 | 0 | 0 |
| ANE PAT | 0 | 0 | 0 | 0 | 0 | 0 |
| Arabis sp. | 0 | 0 | 0 | 0 | 0 | 0 |
| ART FRI | 0 | 5 | 6 | 0 | 0 | 4 |
| ART LUD | 0 | 0 | 0 | 0 | 0 | 0 |
| BOU GRA | 0 | 9 | 19 | 0 | 0 | 0 |
| CAL LON | 0 | 0 | 0 | 0 | 0 | 3 |
| Carex spp. | 23 | 18 | 4 | 3 | 40 | 19 |
| CER ARV | 0 | 4 | 1 | 0 | 0 | 0 |
| ELE COM | 0 | 0 | 0 | 0 | 0 | 0 |
| EQU HYE | 1 | 0 | 0 | 0 | 0 | 0 |
| ERY ASP | 0 | 0 | 0 | 0 | 0 | 0 |
| FES ALT | 0 | 0 | 0 | 0 | 0 | 0 |
| FRA VIR | 0 | 0 | 0 | 0 | 0 | 0 |
| GAL BOR | 0 | 0 | 0 | 0 | 0 | 0 |
| GAU COC | 0 | 0 | 0 | 0 | 0 | 0 |
| GLY LEP | 0 | 0 | 0 | 0 | 0 | 0 |
| HEL HOO | 0 | 0 | 0 | 0 | 0 | 0 |
| HET VIL | 0 | 0 | 0 | 0 | 0 | 0 |
| JUN BAL | 0 | 0 | 0 | 0 | 0 | 0 |
| KOE MAC | 1 | 0 | 14 | 0 | 0 | 3 |
| KRA LAN | 0 | 0 | 0 | 0 | 0 | 0 |
| PHL HOO | 0 | 0 | 0 | 0 | 0 | 0 |
| POA PRA | 38 | 0 | 0 | 4 | 0 | 0 |
| ROS WOO | 4 | 1 | 2 | 1 | 2 | 2 |
| SEL DEN | 0 | 38 | 16 | 0 | 0 | 8 |
| SPO CRY | 0 | 0 | 0 | 0 | 0 | 0 |
| STI COM | 1 | 0 | 6 | 0 | 15 | 16 |
| STI CUR | 0 | 0 | 0 | 0 | 0 | 0 |
| STI VIR | 0 | 0 | 0 | 0 | 0 | 0 |
| SYM OCC | 4 | 1 | 0 | 5 | 1 | 0 |
| VIC AME | 0 | 0 | 0 | 0 | 0 | 0 |

**Appendix 2.** continued.

| | Wilner | | | Coop | | |
|---|---|---|---|---|---|---|
| Sward component | Shrub | Ecotone | Grassland | Shrub | Ecotone | Grassland |
| | Cover (%) | | | | | |
| Snowberry canopy | 82 | 35 | 0 | 65 | 20 | 0 |
| Herbaceous litter | 0 | 25 | 13 | 17 | 40 | 28 |
| Bare ground | 0 | 0 | 3 | 0 | 0 | 5 |
| Shrub litter | 95 | 10 | 0 | 52 | 5 | 0 |
| ACH MIL | 0 | 0 | 0 | 0 | 0 | 0 |
| AGR DAS | 0 | 0 | 0 | 0 | 0 | 0 |
| AGR SMI | 0 | 0 | 3 | 0 | 2 | 0 |
| AGR SUB | 0 | 11 | 1 | 4 | 0 | 1 |
| AND SEP | 0 | 0 | 0 | 0 | 0 | 0 |
| ANE PAT | 0 | 0 | 0 | 0 | 0 | 0 |
| Arabis sp. | 0 | 0 | 0 | 0 | 0 | 0 |
| ART FRI | 0 | 0 | 3 | 0 | 1 | 0 |
| ART LUD | 1 | 0 | 2 | 0 | 0 | 0 |
| BOU GRA | 0 | 0 | 0 | 0 | 0 | 1 |
| CAL LON | 0 | 0 | 0 | 0 | 0 | 0 |
| Carex spp. | 1 | 8 | 10 | 23 | 5 | 10 |
| CER ARV | 0 | 0 | 0 | 0 | 0 | 0 |
| ELE COM | 0 | 0 | 0 | 0 | 0 | 0 |
| EQU HYE | 0 | 0 | 0 | 0 | 0 | 0 |
| ERY ASP | 0 | 0 | 0 | 0 | 0 | 0 |
| FES ALT | 0 | 3 | 0 | 0 | 0 | 0 |
| FRA VIR | 3 | 3 | 0 | 0 | 0 | 0 |
| GAL BOR | 0 | 0 | 0 | 0 | 0 | 0 |
| GAU COC | 0 | 0 | 0 | 0 | 0 | 0 |
| GLY LEP | 0 | 0 | 0 | 1 | 0 | 0 |
| HEL HOO | 0 | 0 | 1 | 0 | 0 | 0 |
| HET VIL | 0 | 0 | 0 | 0 | 0 | 2 |
| JUN BAL | 0 | 0 | 0 | 0 | 2 | 0 |
| KOE MAC | 0 | 0 | 8 | 0 | 3 | 2 |
| KRA LAN | 0 | 0 | 0 | 0 | 0 | 0 |
| PHL HOO | 0 | 0 | 0 | 0 | 0 | 0 |
| POA PRA | 0 | 0 | 0 | 0 | 0 | 0 |
| ROS WOO | 3 | 4 | 1 | 0 | 0 | 0 |
| SEL DEN | 0 | 0 | 12 | 0 | 0 | 0 |
| SPO CRY | 0 | 0 | 0 | 0 | 1 | 2 |
| STI COM | 0 | 21 | 42 | 4 | 49 | 23 |
| STI CUR | 0 | 0 | 0 | 0 | 0 | 0 |
| STI VIR | 0 | 6 | 0 | 0 | 0 | 0 |
| SYM OCC | 5 | 3 | 1 | 5 | 1 | 0 |
| VIC AME | 0 | 0 | 0 | 0 | 0 | 0 |

**Appendix 2.** continued

|  | Matador |  |  |
|---|---|---|---|
| Sward component | Shrub | Ecotone | Grassland |
|  | Cover (%) |  |  |
| Snowberry canopy | 58 | 30 | 0 |
| Herbaceous litter | 20 | 30 | 23 |
| Bare ground | 2 | 0 | 1 |
| Shrub litter | 23 | 5 | 0 |
| ACH MIL | 0 | 0 | 0 |
| AGR DAS | 0 | 9 | 7 |
| AGR SMI | 3 | 0 | 0 |
| AGR SUB | 0 | 0 | 0 |
| AND SEP | 0 | 0 | 0 |
| ANE PAT | 0 | 0 | 0 |
| Arabis sp. | 0 | 0 | 0 |
| ART FRI | 1 | 3 | 9 |
| ART LUD | 0 | 0 | 0 |
| BOU GRA | 0 | 0 | 0 |
| CAL LON | 0 | 0 | 0 |
| Carex spp. | 8 | 18 | 8 |
| CER ARV | 0 | 1 | 0 |
| ELE COM | 0 | 0 | 0 |
| EQU HYE | 0 | 0 | 0 |
| ERY ASP | 0 | 0 | 0 |
| FES ALT | 0 | 0 | 0 |
| FRA VIR | 0 | 0 | 0 |
| GAL BOR | 0 | 0 | 0 |
| GAU COC | 0 | 0 | 0 |
| GLY LEP | 0 | 0 | 0 |
| HEL HOO | 0 | 0 | 0 |
| HET VIL | 0 | 1 | 0 |
| JUN BAL | 0 | 0 | 0 |
| KOE MAC | 2 | 13 | 21 |
| KRA LAN | 4 | 0 | 8 |
| PHL HOO | 1 | 0 | 1 |
| POA PRA | 0 | 0 | 0 |
| ROS WOO | 0 | 0 | 0 |
| SEL DEN | 0 | 0 | 0 |
| SPO CRY | 0 | 0 | 0 |
| STI COM | 0 | 0 | 0 |
| STI CUR | 0 | 0 | 0 |
| STI VIR | 29 | 16 | 23 |
| SYM OCC | 6 | 5 | 0 |
| VIC AME | 0 | 1 | 0 |

**Appendix 3.** Soil bulk density along the gradient from herbaceous to shrub communities in the Mixed Prairie Ecozone of Saskatchewan.

| | | Sandy sites | | | | | | Loamy sites | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plot location | Depth (cm) | Biddulph | Rudy | Montrose N | Montrose S | Coop | **Mean** | Kernen | Abbott | Wilner | Matador | **Mean** |
| | | Bulk density (g $cm^{-3}$) | | | | | | | | | | |
| Shrub 1 | 0-3 | 1.2 | 0.9 | 0.9 | 1.1 | 1.1 | **1.0** | 0.5 | 0.5 | 0.5 | 0.6 | **0.5** |
| | 3-10 | 1.4 | 1.1 | 1.3 | 1.0 | 1.4 | **1.2** | 1.0 | 0.6 | 0.7 | 0.9 | **0.8** |
| | 10-20 | 1.2 | 1.5 | 1.3 | 1.4 | 1.5 | **1.4** | 1.2 | 0.8 | 1.0 | 0.9 | **1.0** |
| | 20-30 | 1.4 | 1.5 | 1.4 | 1.3 | 1.5 | **1.4** | 1.2 | 1.2 | 0.9 | 1.2 | **1.1** |
| | 30-40 | 1.4 | 1.4 | 1.6 | 1.4 | 1.5 | **1.4** | 1.2 | 1.4 | 1.0 | 1.1 | **1.2** |
| | 40-50 | 1.3 | 1.5 | 1.6 | 1.3 | 1.6 | **1.5** | 1.2 | - | 1.0 | 1.1 | **1.1** |
| Shrub 2 | 0-3 | 0.7 | 0.6 | 0.8 | 1.0 | 1.0 | **0.8** | 0.6 | 0.5 | 0.6 | 0.8 | **0.6** |
| | 3-10 | 1.3 | 1.3 | 1.4 | 1.2 | 1.3 | **1.3** | 0.9 | 0.9 | 0.9 | 1.0 | **0.9** |
| | 10-20 | 1.4 | 1.1 | 0.4 | 1.4 | 1.4 | **1.1** | 1.0 | 1.3 | 0.9 | 1.0 | **1.0** |
| | 20-30 | 1.6 | 1.4 | 1.4 | 1.4 | 1.5 | **1.5** | 1.2 | 1.4 | 1.0 | 1.1 | **1.2** |
| | 30-40 | 1.5 | 1.4 | 1.6 | 1.2 | 1.5 | **1.4** | 1.2 | 1.4 | 1.1 | 1.1 | **1.2** |
| | 40-50 | 1.4 | 1.3 | 1.6 | 1.2 | 1.7 | **1.4** | 1.1 | - | 0.9 | 1.2 | **1.1** |
| Shrub 3 | 0-3 | 1.0 | 1.0 | 1.0 | 0.8 | 1.1 | **0.9** | 0.5 | 0.6 | 0.6 | 0.8 | **0.6** |
| | 3-10 | 1.2 | 1.1 | 1.4 | 1.3 | 1.5 | **1.3** | 0.7 | 0.9 | 0.9 | 1.0 | **0.9** |
| | 10-20 | 1.6 | 1.4 | 1.4 | 1.3 | 1.5 | **1.4** | 0.7 | 1.3 | 1.1 | 0.9 | **1.0** |
| | 20-30 | 1.5 | 1.6 | 1.5 | 1.4 | 1.5 | **1.5** | 0.9 | 1.3 | 0.8 | 1.0 | **1.0** |
| | 30-40 | 1.5 | 1.4 | 1.5 | 1.4 | 1.6 | **1.5** | 1.1 | 1.4 | 0.9 | 1.0 | **1.1** |
| | 40-50 | 1.4 | 1.4 | 1.5 | 1.3 | 1.7 | **1.5** | 1.2 | - | 1.0 | 1.0 | **1.1** |
| Ecotone | 0-3 | 1.0 | 0.8 | 1.2 | 0.7 | 1.2 | **1.0** | 0.8 | 0.4 | 0.8 | 0.9 | **0.7** |
| | 3-10 | 1.4 | 1.3 | 1.5 | 1.2 | 1.5 | **1.4** | 1.0 | 0.8 | 1.0 | 0.9 | **0.9** |
| | 10-20 | 1.4 | 1.4 | 1.4 | 1.3 | 1.4 | **1.4** | 0.9 | 1.4 | 1.2 | 0.9 | **1.1** |
| | 20-30 | 1.6 | 1.4 | 1.6 | 1.4 | 1.5 | **1.5** | 1.1 | 1.4 | 1.2 | 0.9 | **1.1** |
| | 30-40 | 1.5 | 1.4 | 1.5 | 1.4 | 1.6 | **1.5** | 1.3 | 1.3 | 1.1 | 1.0 | **1.2** |
| | 40-50 | 1.6 | 1.5 | 1.5 | 1.5 | 1.5 | **1.5** | 1.2 | - | 1.2 | 1.2 | **1.2** |
| Grassland 1 | 0-3 | 0.9 | 0.8 | 1.2 | 1.1 | 1.2 | **1.0** | 0.6 | 0.7 | 0.8 | 0.9 | **0.7** |
| | 3-10 | 1.1 | 1.2 | 1.5 | 1.3 | 1.4 | **1.3** | 0.8 | 1.1 | 1.2 | 1.0 | **1.0** |
| | 10-20 | 1.4 | 1.4 | 1.4 | 1.5 | 1.6 | **1.5** | 1.1 | 1.3 | 1.1 | 1.1 | **1.2** |
| | 20-30 | 1.5 | 1.5 | 1.4 | 1.3 | 1.5 | **1.4** | 1.2 | 1.4 | 1.3 | 1.0 | **1.2** |
| | 30-40 | 1.5 | 1.4 | 1.4 | 1.5 | 1.6 | **1.5** | 1.1 | 1.4 | 1.3 | 1.1 | **1.2** |
| | 40-50 | 1.5 | 1.1 | 1.5 | 1.5 | 1.7 | **1.5** | 1.2 | - | 1.2 | 1.2 | **1.2** |
| Grassland 2 | 0-3 | 1.1 | 0.9 | 1.1 | 1.3 | 1.3 | **1.1** | 0.5 | 0.6 | 0.8 | 1.0 | **0.7** |
| | 3-10 | 1.0 | 1.2 | 1.3 | 1.3 | 1.6 | **1.3** | 0.9 | 1.0 | 1.0 | 1.1 | **1.0** |
| | 10-20 | 1.3 | 1.4 | 1.4 | 1.5 | 1.7 | **1.5** | 1.2 | 1.1 | 1.3 | 1.1 | **1.2** |
| | 20-30 | 1.3 | 1.3 | 1.5 | 1.3 | 1.6 | **1.4** | 1.2 | 1.4 | 1.4 | 1.1 | **1.2** |
| | 30-40 | 1.4 | 1.4 | 1.5 | 1.3 | 1.6 | **1.5** | 1.2 | 1.2 | 1.3 | 1.1 | **1.2** |
| | 40-50 | 1.5 | 1.4 | 1.4 | 1.4 | 1.6 | **1.5** | 1.2 | - | 1.3 | 1.0 | **1.2** |

**Appendix 4.** Soil texture in grazed and ungrazed grassland in the Mixed Prairie Ecozone of Saskatchewan.

| Site and grazing treatment | Treatment | % Sand | % Silt | % Clay | Texture class |
|---|---|---|---|---|---|
| Matador North Ungrazed | 1 | 24 | 26 | 50 | C |
| | 2 | 24 | 18 | 58 | C |
| | 3 | 24 | 20 | 56 | C |
| | 4 | 22 | 22 | 56 | C |
| | 5 | 22 | 24 | 54 | C |
| | 6 | 20 | 22 | 58 | C |
| Matador North Grazed | 1 | 24 | 24 | 52 | C |
| | 2 | 24 | 24 | 52 | C |
| | 3 | 24 | 26 | 50 | C |
| | 4 | 24 | 28 | 48 | C |
| | 5 | 24 | 22 | 54 | C |
| | 6 | 22 | 22 | 56 | C |
| Matador South Ungrazed | 1 | 34 | 38 | 28 | CL |
| | 2 | 34 | 38 | 28 | CL |
| | 3 | 30 | 32 | 38 | CL |
| | 4 | 32 | 38 | 30 | CL |
| | 5 | 30 | 36 | 34 | CL |
| | 6 | 32 | 38 | 30 | CL |
| Matador South Grazed | 1 | 30 | 28 | 42 | C |
| | 2 | 30 | 32 | 38 | CL |
| | 3 | 34 | 38 | 28 | CL |
| | 4 | 30 | 38 | 32 | CL |
| | 5 | 32 | 38 | 30 | CL |
| | 6 | 28 | 32 | 40 | CL |
| Biddulph Ungrazed | 1 | 88 | 8 | 4 | S |
| | 2 | 88 | 8 | 4 | S |
| | 3 | 87 | 9 | 4 | S |
| | 4 | 85 | 11 | 4 | S |
| | 5 | 90 | 7 | 3 | S |
| | 6 | 87 | 10 | 3 | S |
| Biddulph Grazed | 1 | 82 | 15 | 3 | LS |
| | 2 | 81 | 16 | 3 | LS |
| | 3 | 89 | 8 | 3 | S |
| | 4 | 85 | 12 | 3 | S |
| | 5 | 86 | 11 | 3 | S |
| | 6 | 85 | 12 | 3 | S |
| Kernen Ungrazed | 1 | 72 | 18 | 10 | SL |
| | 2 | 74 | 16 | 10 | SL |
| | 3 | 72 | 18 | 10 | SL |
| | 4 | 68 | 24 | 8 | SL |
| | 5 | 70 | 22 | 8 | SL |
| | 6 | 72 | 18 | 10 | SL |

**Appendix 4.** Continued.

| Site and grazing treatment | Plot | % Sand | % Silt | % Clay | Texture class |
|---|---|---|---|---|---|
| Kernen Grazed | 1 | 30 | 58 | 12 | SiL |
| | 2 | 40 | 36 | 24 | LS |
| | 3 | 32 | 50 | 18 | LS |
| | 4 | 34 | 50 | 16 | LS |
| | 5 | 32 | 40 | 28 | LS |
| | 6 | 28 | 36 | 36 | CL |
| Macrorie Ungrazed | 1 | 58 | 32 | 10 | SL |
| | 2 | 62 | 28 | 10 | SL |
| | 3 | 66 | 26 | 8 | SL |
| | 4 | 68 | 24 | 8 | SL |
| | 5 | 62 | 26 | 12 | SL |
| | 6 | 62 | 30 | 8 | SL |
| Macrorie Grazed | 1 | 42 | 38 | 20 | LS |
| | 2 | 46 | 36 | 18 | LS |
| | 3 | 36 | 44 | 20 | LS |
| | 4 | 42 | 40 | 18 | LS |
| | 5 | 44 | 32 | 24 | LS |
| | 6 | 52 | 30 | 18 | LS |
| Monet Ungrazed | 1 | 54 | 26 | 20 | LS |
| | 2 | 42 | 42 | 16 | LS |
| | 3 | 42 | 40 | 18 | LS |
| | 4 | 42 | 40 | 18 | LS |
| | 5 | 48 | 36 | 16 | LS |
| | 6 | 46 | 36 | 18 | LS |
| Monet Grazed | 1 | 52 | 36 | 12 | LS |
| | 2 | 54 | 24 | 22 | SCL |
| | 3 | 46 | 38 | 16 | LS |
| | 4 | 46 | 34 | 20 | LS |
| | 5 | 48 | 38 | 14 | LS |
| | 6 | 48 | 36 | 16 | LS |
| Outlook Ungrazed | 1 | 87 | 9 | 4 | S |
| | 2 | 89 | 7 | 4 | S |
| | 3 | 88 | 9 | 3 | S |
| | 4 | 88 | 9 | 3 | S |
| | 5 | 91 | 6 | 3 | S |
| | 6 | 91 | 5 | 4 | S |
| Outlook Grazed | 1 | 59 | 35 | 6 | SL |
| | 2 | 59 | 35 | 6 | SL |
| | 3 | 60 | 33 | 7 | SL |
| | 4 | 65 | 29 | 6 | SL |
| | 5 | 58 | 36 | 6 | SL |
| | 6 | 62 | 33 | 5 | SL |
| Kindersley Ungrazed | 1 | 14 | 28 | 58 | C |
| | 2 | 14 | 28 | 58 | C |
| | 3 | 20 | 28 | 52 | C |
| | 4 | 14 | 30 | 56 | C |
| | 5 | 14 | 30 | 56 | C |
| | 6 | 14 | 30 | 56 | C |

**Appendix 4.** Continued.

| Site and grazing treatment | Plot | % Sand | % Silt | % Clay | Texture class |
|---|---|---|---|---|---|
| Kindersley Grazed | 1 | 14 | 26 | 60 | C |
| | 2 | 16 | 24 | 60 | C |
| | 3 | 14 | 22 | 64 | HC |
| | 4 | 14 | 28 | 58 | C |
| | 5 | 12 | 30 | 58 | C |
| | 6 | 16 | 32 | 52 | C |
| Aberdeen Ungrazed | 1 | 36 | 50 | 14 | LS |
| | 2 | 42 | 42 | 16 | LS |
| | 3 | 30 | 56 | 14 | SiL |
| | 4 | 40 | 46 | 14 | LS |
| | 5 | 50 | 40 | 10 | LS |
| | 6 | 36 | 48 | 16 | LS |
| Aberdeen Grazed | 1 | 50 | 42 | 8 | LS |
| | 2 | 44 | 48 | 8 | LS |
| | 3 | 48 | 44 | 8 | LS |
| | 4 | 48 | 42 | 10 | LS |
| | 5 | 48 | 44 | 8 | LS |
| | 6 | 42 | 44 | 14 | LS |

**Appendix 5.** Mean percent plant and ground cover in grazed and ungrazed grassland communities at study sites in the Prairie Ecozone in July 2003. Values are means of 8 quadrats per plot with 6 plots located in each grazed and ungrazed study site.

| | Matador S | | Matador N | | Kernen | | Macrorie | | Biddulph | | Monet | | Outlook | | Kindersley | | Abbott | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | U | G | U | G | U | G | U | G | U | G | U | G | U | G | U | G | U | G |
| Bare | 0 | 2.1 | 0 | 25 | 0 | 7.8 | 0 | 2.5 | 0.9 | 7.1 | 0 | 0 | 7.3 | 73 | 0.7 | 37 | 0.1 | 1.1 |
| Litter | 86 | 8.9 | 84 | 25 | 26 | 2.2 | 54 | 0.4 | 40 | 0.4 | 35 | 0 | 33 | 0.2 | 69 | 32 | 22 | 0.5 |
| ACH MIL | 0 | 0 | 0.1 | 0.1 | 0.3 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.3 | 0 | 0 |
| AGR SMI | 0.3 | 0.4 | 0 | 0 | 2.2 | 0.6 | 0 | 0 | 2.4 | 0 | 0 | 0 | 0 | 0.3 | 0.1 | 0 | 1.9 | 0 |
| AGR SUB | 0 | 0 | 0 | 0 | 0.5 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.1 | 0 |
| AGR TRA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 12 | 5.4 | 0 |
| AGR ALB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 |
| AND SEP | 0 | 0.1 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 |
| ANE PAT | 1 | 0 | 0 | 0 | 0.9 | 0 | 2.9 | 0.5 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 2.6 | 1.3 |
| ANT APR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.2 |
| Arabis sp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0 |
| ARA HIR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.2 | 0 | 0 |
| ART CAM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | 0 | 0 |
| ART FRI | 1 | 2.3 | 1.7 | 3.9 | 6.4 | 28 | 3.9 | 13 | 8.3 | 11 | 1.5 | 3.8 | 4 | 0.3 | 5 | 6.4 | 1.8 | 16 |
| ART LUD | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ART CAN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.3 | 0 | 0 | 0 | 0 | 0 |
| AST ERI | 0 | 0 | 0.2 | 0.1 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Aster sp. | 0 | 0 | 0.5 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AST AME | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 |
| AST BIS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| AST DAS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 |
| AST LAE | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AST MIS | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0.7 |
| AST PEC | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BOU GRA | 0.1 | 9.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 1.3 | 0.2 | 0 | 0.8 | 0 | 0 | 0 | 0 | 0.2 |
| CAL LON | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.2 | 2.7 | 0 | 0 | 0 | 0 |
| CAL MON | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CAR FIL | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 1.6 | 0 | 0 | 0 | 24 | 0 | 0 | 0 | 0 | 0 |
| Carex spp. | 1.5 | 13 | 2.6 | 5.6 | 11 | 47 | 10 | 4.7 | 6.1 | 0 | 2.5 | 9.9 | 0.6 | 2.7 | 2 | 1.7 | 14 | 8.9 |
| CER ARV | 0 | 0 | 0 | 0 | 0.1 | 0 | 0.2 | 0 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CHA ERE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CHE ALB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 |
| COM PAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 |
| DAL PUR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DES SOP | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EAL COM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 |
| ELY LAN | 8.8 | 0.2 | 18 | 17 | 4.7 | 1 | 16 | 0.9 | 0 | 0 | 4.8 | 0.5 | 1.8 | 1.8 | 3.5 | 0 | 9.1 | 5.2 |
| ERI CAE | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| ERY ASP | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 |
| EUR LAN | 0 | 0 | 9.1 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.9 | 2.7 | 0 | 0 |
| FES ALT | 0 | 0 | 0 | 0 | 17 | 0 | 2.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4.9 | 0 |

**Appendix 5.** Continued.

| | Matador S | | Matador N | | Kernen | | Macrorie | | Biddulph | | Monet | | Outlook | | Kindersley | | Abbott | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | U | G | U | G | U | G | U | G | U | G | U | G | U | G | U | G | U | G |
| GAL BOR | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 |
| GAU COC | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GEU TRI | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0.1 |
| GRI SQU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GUT SAR | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 |
| HEL HOO | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 4.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.2 | 0 |
| HEL ANU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 |
| HES COM | 0 | 7.1 | 0 | 0 | 0 | 14 | 16 | 16 | 34 | 5.2 | 45 | 14 | 25 | 7.4 | 0 | 0 | 0 | 28 |
| HET VIL | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1.5 | 0 | 0 | 0 | 0.7 | 0 | 0 | 0 | 0.4 |
| KOE MAC | 0.9 | 2.1 | 2 | 15 | 0.1 | 0 | 0.1 | 0.6 | 3.8 | 0.1 | 0.2 | 1.1 | 2.2 | 0 | 0 | 0.1 | 1 | 2.4 |
| LAP SQU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LEP DEN | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LES ARE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LIA PUN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0.4 | 0 | 0 | 0 | 0 | 0 |
| LIC HEN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 7.8 | 0 | 0 |
| LIN LEW | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 |
| LIN RIG | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 |
| LIT RUD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.5 | 0 | 0 | 0 | 0 |
| LYG JUN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MAL COC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0.6 | 0.7 | 0 | 0 |
| MAM VIV | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| MED SAT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.3 | 0 | 0 | 0 | 0 |
| MIR HIR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MUS DIV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NAS VIR | 17 | 5.9 | 4.9 | 2.8 | 4.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0 | 0 |
| ORO FAS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 |
| OXY SER | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 |
| PEN NIT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| PHL HOO | 0.3 | 2.3 | 0.6 | 1.9 | 0.1 | 0.1 | 0.2 | 2.2 | 0.1 | 0 | 0.6 | 0.7 | 0 | 0 | 0.1 | 0.1 | 0 | 1.6 |
| POA PRA | 0 | 0 | 0 | 0 | 4.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.9 | 0 |
| POA SEC | 0 | 0 | 0 | 0 | 0 | 2.5 | 0 | 1.3 | 0 | 0 | 0.1 | 1.4 | 0 | 0 | 0 | 0 | 0.1 | 0 |
| POT PEN | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0.2 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 2.5 |
| PSO ARG | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| PSO LAN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.9 | 1.8 | 0 | 0 | 0 | 3.2 | 0 | 0 | 0 | 0 |
| ROS WOO | 0 | 0 | 0 | 0 | 0.5 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.5 | 0 | 0 | 0.3 | 0 |
| SAL KAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 |
| SEL DEN | 1.9 | 52 | 0 | 0 | 0 | 5.1 | 0.1 | 60 | 6.8 | 80 | 12 | 68 | 0 | 0 | 0 | 0 | 1.6 | 35 |
| SOL MIS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.3 | 0 | 0 | 0 | 0.6 |
| SPH COC | 0 | 2.4 | 0.1 | 1.3 | 0 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SPO CRY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 |
| STI SPA | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 0 |
| SYM OCC | 0 | 0 | 0 | 0.1 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0 | 0 | 0 | 0 |
| TRA DUB | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| VIC AME | 0.1 | 0 | 0.9 | 0.4 | 0.6 | 0 | 0.5 | 0 | 0 | 0 | 0.1 | 0 | 0.1 | 0 | 0 | 0 | 0.2 | 0 |